FINAL REPORT

Underwater Simultaneous EMI and Magnetometer System (USEMS)

ESTCP Project MR-200733

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14. ABSTRACT

Due to historical training and disposal activity, Munitions and Explosives of Concern (MEC) exist in the marine environment in a variety of underwater topographies ranging from open waters to bays to port areas to lakes and ponds. Although the geophysical sensors used for MEC detection in the marine environment – magnetometers and pulsed EM – are the same as those used in the terrestrial environment, there is not a one-size-fits-all solution due to differences in water depth. Cable-towed arrays are effective in large open areas, but may have difficulty operating in shallow or constrained areas. Project MM-0733, the Underwater Simultaneous EMI and Magnetometer System (USEMS) deploys a single total field magnetometer and commercial-off-the-shelf (COTS) EM61 submersible coil, with both sensors configured in a hydrodynamically smooth towfish rigidly attached behind a small boat via a six-meter boom whose angles are instrumented to provide a direct measurement of the sensors' locations. USEMS was demonstrated near Plum Tree Island (Hampton) VA in September 2010.

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UXO, MEC, underwater, detection, magnetometer, EM61

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List of Acronyms

BRAC:	Base Realignment and Closure
CEHNC:	US Army Corps of Engineers Engineering and Support Center, Huntsville
COTS:	Commercial Off The Shelf
CRADA:	Cooperative Research and Development Agreement
CSM:	Conceptual Site Model
DGM:	Digital Geophysical Mapping
DSB:	Defense Sciences Board
EM:	Electromagnetic
EMI:	Electromagnetic Induction
FUDS:	Formerly Used Defense Sites
GPS:	Global Positioning System
MEC:	Munitions and Explosives of Concern
MPC:	Magnetometer Period Counter
MPI:	Man-Portable Interleaving
MSEMS:	Man-Portable Simultaneous EMI and Magnetometer System
MTA:	Marine Towed Array
NACA:	National Advisory Committee for Aeronautics
NMEA:	National Marine Electronic Association
NOAA:	National Oceanographic and Atmospheric Administration
PLC:	Programmable Logic Controller
RPS:	Rotary Position Sensor
RTK:	Real Time Kinematic
RTN:	Real Time Network
SEMS:	Simultaneous EMI and Magnetometer System
STOLS:	Surface Towed Ordnance Location System
USACE:	US Army Corps of Engineers
USEMS:	Underwater Simultaneous EMI and Magnetometer System
UXO:	Unexploded Ordnance
VSP:	Visual Sample Plan

Acknowledgments

The authors would like to thank the ESTCP program office, Dr. Roy Richard from SAIC for the system's overall mechanical design, Roger Race and Davis Sanford from Brooke Ocean Technology for their assistance in designing and testing the towfish, and John Morris from SAIC for his assistance in fielding the system.

Executive Summary

The Underwater Simultaneous EMI and Magnetometer System (USEMS) consists of a towfish housing an EM61 submersible coil and a total field magnetometer towed by a 17’ boat. The towfish is attached to the transom of the boat with a rigid carbon fiber boom whose rotational degrees of freedom are instrumented with encoders to directly measure its yaw, pitch and roll relative to the back of the boat. The magnetometer and EM61 are operated concurrently via the interleaving technique developed and demonstrated under ESTCP projects MM-0208 and MM-0414. USEMS is designed to survey shallow (3’ to 12’) water such as lakes, ponds, rivers, streams, coastlines, and obstructed areas where a larger cable-towed array is not able to navigate. In September 2010 the system was demonstrated at Plum Tree Island, VA where it surveyed a shallow water test site and a deeper water test site, and acquired traverse data off Plum Tree Island. The magnetometer was effective at detecting objects at standoff distances of 0.5m, 1.0m, and 1.5m off the bottom. The EM61 was effective at detecting objects at a standoff distance of 0.5m off the bottom. In very shallow water, the towfish had a slight vertical oscillation, but this vanished in deeper water and thus is likely due to interaction with the boat motor’s propeller wash. The system can be used to survey tightly-spaced parallel tracks provided that wind and wave states are mild and provided that a GPS antenna feeding a track guidance system is deployed in the bow of the boat. The approximate cost to build a USEMS is $240k. Approximate survey costs for USEMS and a two-person crew are $1440 per hectare.

1 INTRODUCTION

1.1 BACKGROUND

Due to historical training and disposal activity, Munitions and Explosives of Concern (MEC) exist in the marine environment in a variety of underwater topographies ranging from open waters to bays to port areas to lakes and ponds. Although the geophysical sensors used for MEC detection in the marine environment – magnetometers and pulsed EM – are the same as those used in the terrestrial environment, there is not a one-size-fits-all solution due to differences in water depth. Cable-towed arrays are effective in large open areas, but may have difficulty operating in shallow or constrained areas. Project MM-0733, the Underwater Simultaneous EMI and Magnetometer System (USEMS) deploys a single total field magnetometer and commercial-off-the-shelf (COTS) EM61 submersible coil, with both sensors configured in a hydrodynamically smooth towfish. The towfish is rigidly attached behind a 17’ Carolina Skiff via a six-meter boom whose angles are instrumented to provide a direct measurement of the sensors’ locations. USEMS was demonstrated near Plum Tree Island (Hampton) VA in September 2010.

1.2 OBJECTIVE OF THE DEMONSTRATION

The requirements of the demonstration were to verify and validate:

- The hydrodynamic stability of USEMS’ submerged towfish
- The ability of USEMS to maintain a constant height above bottom
- The accuracy of the geodetically combined sensor and positioning data
- The ability of USEMS to cover an area with parallel swaths
- The general ease of operation of the system

To meet these objectives, we identified a shallow (chest-high) section off Plum Tree Island free of metallic clutter, emplaced a test plot with 14 pipes ranging from 1.5” to 4” in diameter, measured the locations of items in it with RTK GPS, and surveyed the test plot multiple times. We also surveyed a second deeper test plot where objects were placed but their precise locations were not directly measured with RTK GPS. Finally, we ran traverses off Plum Tree Island in areas of previously identified metallic contamination.

1.3 REGULATORY DRIVERS

The primary driver is the continued need to develop tools to detect underwater MEC. The documented use of a pole-mounted concurrent mag/EM system will allow other contractors to employ this technique.

2 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

USEMS consists of the following major systems:

- Boat
- Boom with bridle and transom mount
- Towfish with geophysical sensors (magnetometer and EM coil)
- Dive planes for depth control
- Positioning sensors
- Topside electronics

These are shown in the figure below.

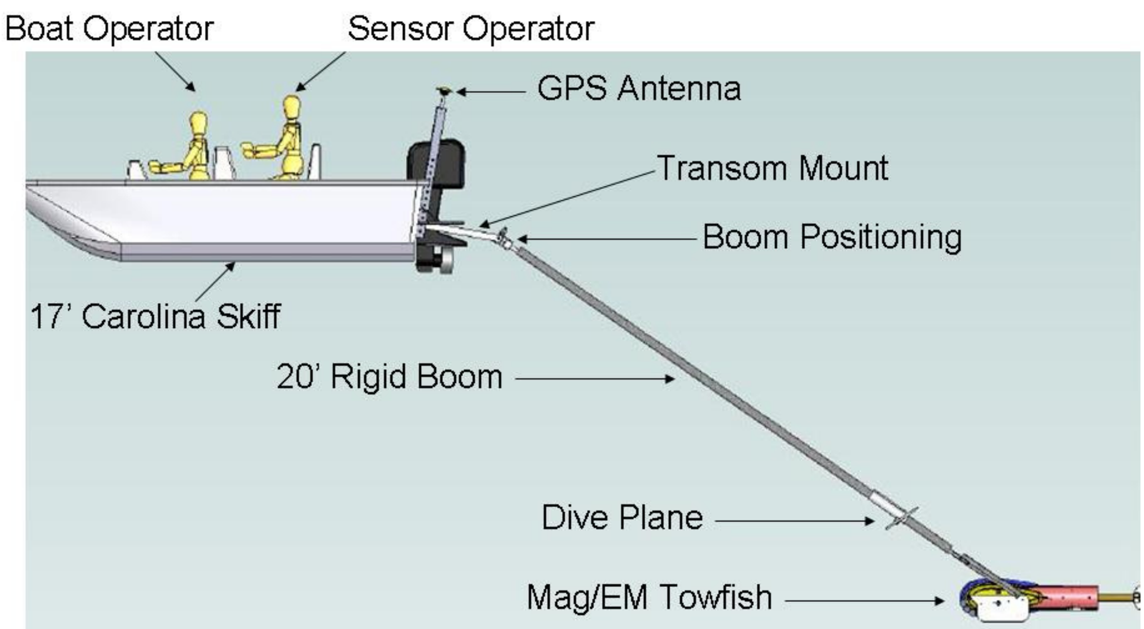

Figure 1: USEMS schematic

The boat is a 17' Carolina Skiff with a V-shaped hull. A mount on the transom of the boat hosts the boom. The attachment point of the boom to the transom allows the boom to pivot freely in yaw (azimuth angle), pitch (incidence angle), and roll (twist).

The towfish contains a commercial-off-the-shelf (COTS) EM61-S (submersible) coil and a Geometrics G-882 total field magnetometer with integrated depth and altitude sensors (the G-882 magnetometer was special-ordered from Geometrics with a Larmor output, as the technical approach of interleaving magnetometer data between EM61 pulses requires the interleaving electronics to have access to the magnetometer's Larmor signal). The towfish is attached to the wet end of the boom via a rigid bridle.

Hydraulically-driven dive planes on the boom are used to drive the towfish up and down in the water column to adjust the desired height off the bottom. The dive planes are operated manually via an operator-driven joystick.

Positioning sensors include a) a dual-antenna GPS in the boat which provides the location of the transom as well as the boat's heading; b) an inclinometer in the boat measuring the boat's pitch and roll; c) three Rotary Positioning Sensors (RPS) at the boom's transom attachment point measuring the boom's yaw, pitch, and roll; d) an RPS at the point where the bridle attaches to the end of the boom, measuring the bridle's yaw; e) an inclinometer in the fish, measuring its pitch and roll, and f) a depth sensor and an altimeter in the fish. An ancillary depth sensor is deployed in the boat to measure the depth of the water being entered. The actual positioning calculation is performed in post-processing.

Topside electronics include the COTS EM electronics console, the custom Man-Portable Interleaving (MPI) electronics that interleave the magnetometer data between EM61 pulses (sampling the magnetometer only when the EM61 is quiet), a COTS data acquisition computer running Geometrics' commercial MagLog data acquisition software that acquires and time-stamps all sensor data, a COTS depth profiler that also provides general marine navigation support, and a COTS track guidance device.

A chronological summary of the development of the technology is below.

- 1/2008. Preliminary design complete.
- 4/2008. Detailed design complete.
- 8/2008. Design approved by ESTCP.
- 5/2009. Contractual interruption.
- 10/2009. Contract and funding restarted.
- 10/2009. First in-water test of fish and bridle to fine-tune buoyancy and verify hydrodynamic stability.
- 5/2010. Demonstration plan accepted by ESTCP.
- 6/2010. Commissioning.
- 7/2010. Stability and depth testing.
- 8/2010. Full water trials
- 9/2010. Plum Tree Island Demonstration.

2.2 TECHNOLOGY DEVELOPMENT

Technology development in USEMS occurred in the following areas:

- The mag/EM61 towfish
- The mechanical attachment system (bridle, boom, and transom mount)
- The depth control system
- The geolocation system
- The data acquisition system

The above were presented in the detailed system design document[1] and were discussed in detail at interim program reviews. They will be summarized briefly.

Mag/EM61 Towfish: The design of the mag/EM61 towfish was based on an earlier EM61-only towfish (figure 2) that SAIC had designed for USACE. This EM61-only fish was based on a hydrodynamically smooth NACA0027 foil, and had been shown to be stable in underwater flight.

Figure 2: EM61-only towfish designed and fabricated for USACE

The USEMS mag/EM61 towfish employed the design of the NACA foil-shaped shell wrapping the EM61 coil from the EM61-only towfish, and added a Geometrics 882 magnetometer with integrated depth and altitude sensors. Although the design of the foil was reused, a new mechanical structure was employed to accommodate the magnetometer. The completed fish is shown below.

[1] MM-0733 USEMS Detailed Design, accepted by ESTCP 8/2008

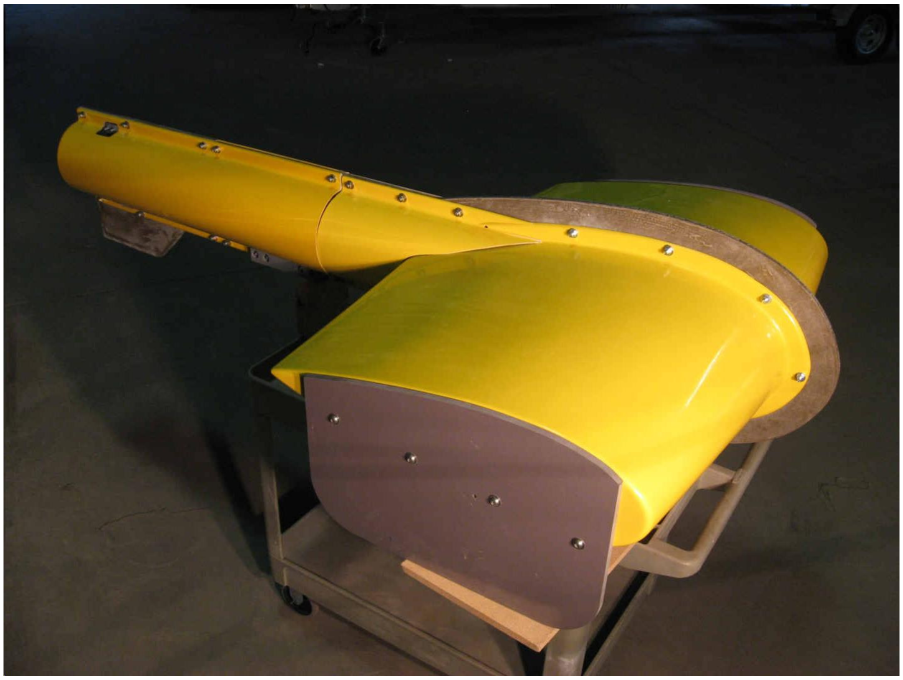

Figure 3: USEMS Mag/EM61 towfish

A photo of the fish bereft of its foil and cladding is shown below. In addition to showing the Geonics EM61 submersible coil and Geometrics G-882 magnetometer, the figure below shows the basic internal mechanical structure of the fish, which employs a central composite backbone to host both the coil and the magnetometer. An inclinometer housed in a PVC case is located behind the EM61 coil. A cutout is present in the backbone to ensure lack of interference with the altitude sensor. A tail fin is employed as a vertical stabilizer.

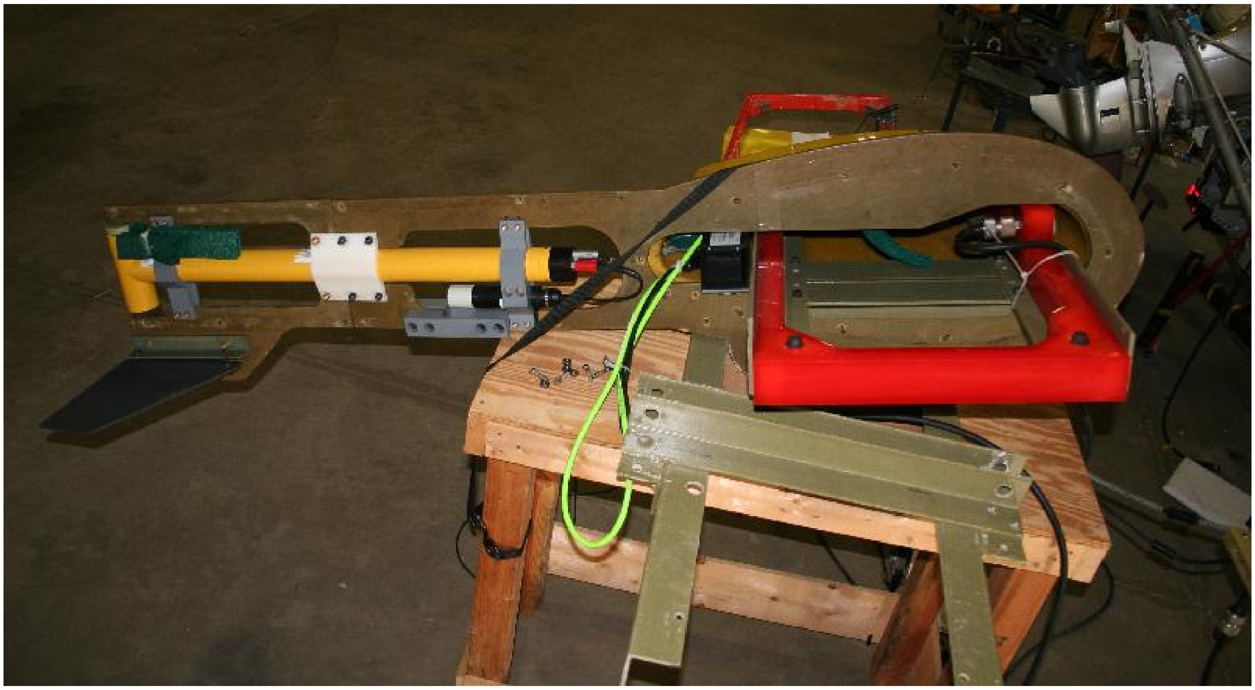

Figure 4: Mag/EM61 towfish internal components

Mechanical Attachment: The mechanical attachment utilizes a carbon fiber bridle, a carbon fiber boom, an aluminum transom mount, and a boom pivot. The bridle (figure 5) is attached to the fish's center of buoyancy, and affixed to the end of the six-meter boom via a pivot and shear pin. The fish, bridle, and boom (figure 6) are attached to the boom pivot (figure 7), which is attached to the transom mount (figure 8). The transom mount is permanently attached to the transom of the boat. The boom pivot contains three Rotary Positioning Sensors (RPS) to accurately measure the yaw, pitch, and roll of the boom.

Figure 5: Towfish, bridle, and boom

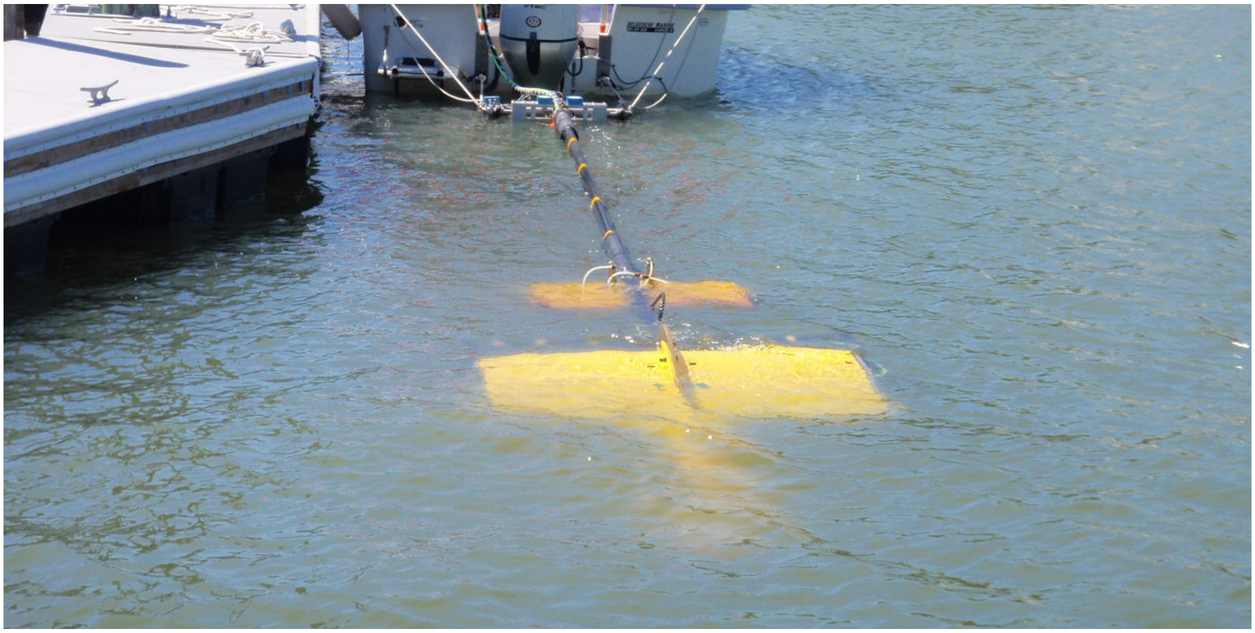

Figure 6: Towfish, bridle, and boom deployed on USEMS boat

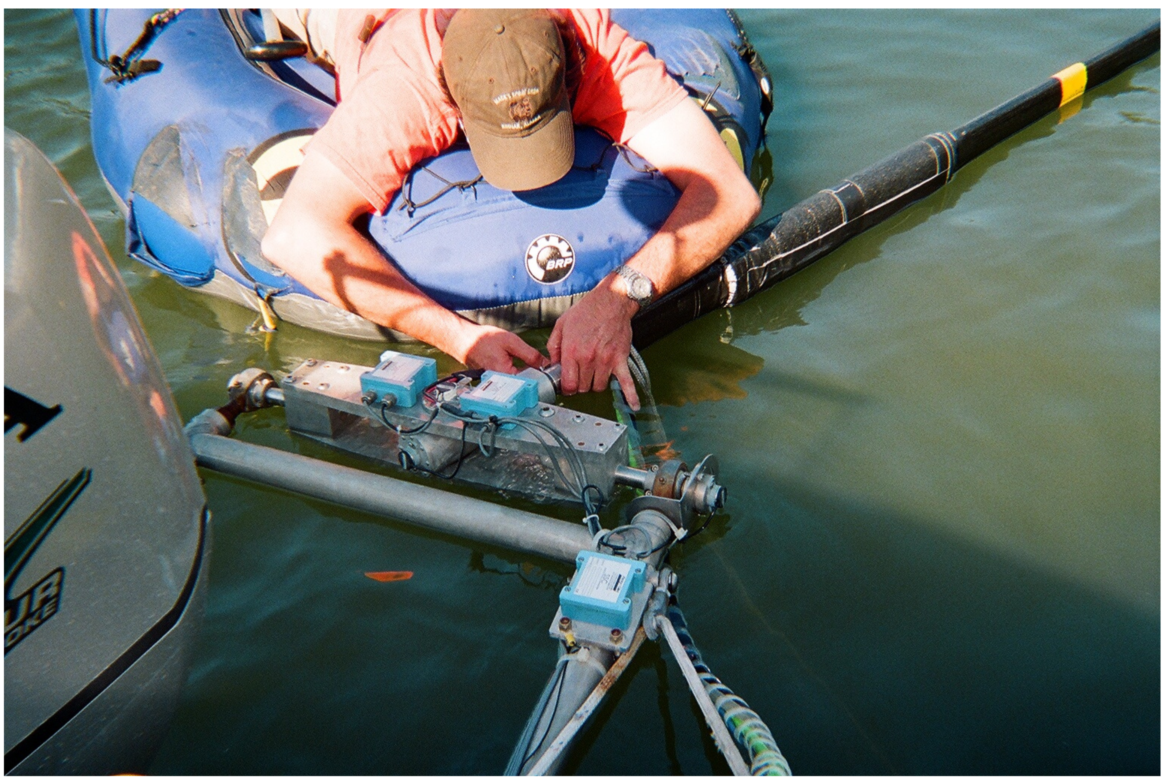

Figure 7: Boom attached to boom pivot

Figure 8: Transom mount attached to boat

Depth Control System: A pair of dive planes (figure 9) is mounted on the boom. The angle of the dive planes is controlled by a joystick which toggles a motor that forces hydraulic fluid down the boom and drives hydraulic cylinders governing the dive plane angle.

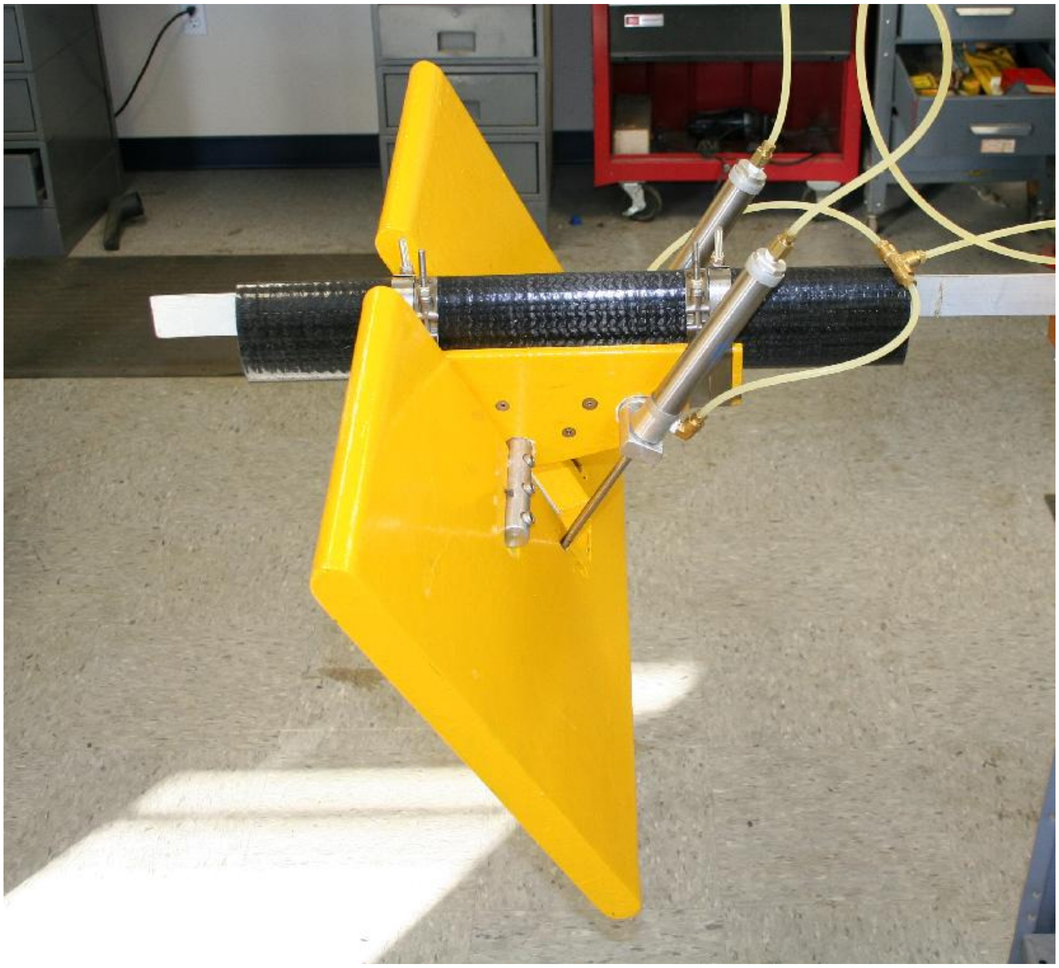

Figure 9: Dive planes

Geolocation System: USEMS uses a Trimble MS860II GPS heading receiver with two antennas. The primary antenna is mounted at the stern of the boat, above the boom pivot point. The secondary antenna is located in the bow of the boat, along the centerline. The MS860II provides the position of the primary antenna, and the heading determined by the vector between the two antennas. RTK positional accuracy (quoted as 2cm) is obtained through use of a base station or corrections broadcast over a Real Time Network (RTN). The heading calculation performed internally by the MS860II uses the "moving base" technique and thus does not require a base station. Three RPS devices with 12-bit precision are used in the boom pivot, allowing direct measurement of the boom's pitch, yaw, and roll. A fourth RPS is mounted at the bridle attachment point to measure the bridle yaw in case the shear pin breaks. An inclinometer is mounted on the boat to measure its pitch and roll, and a second inclinometer is mounted inside the towfish. The quoted accuracies of the heading, RPS, and inclinometers are all 0.1 degrees. The geolocation calculation (a forward kinematic model combining GPS location of the stern antenna, boat heading, boat pitch and roll, boom pitch and roll, bridle yaw, and fish pitch and roll) is performed in post-processing using custom software.

Data Acquisition System: Three separate isolated battery stacks power the EM61, magnetometer, and computer/GPS/ancillary sensors. Optical isolators are employed on the serial connections to eliminate ground loops. Geometrics' COTS software package MagLog is used to acquire serial data from the geophysical sensors (magnetometer and EM61), the positioning sensors (GPS position and heading, the four RPS values, and the inclinometers on the boat and fish), and the ancillary water sensors (boat water depth and fish altitude and depth). The geophysical sensors, GPS, inclinometers, and water sensors provide a direct serial input to MagLog. The RPS devices are interfaced to a Programmable Logic Controller (PLC) that converts their data to a serial format for MagLog to read. In addition, the MagLog computer has a GPS clock board that directly supplies MagLog the GPS time. This eliminates the drift and precision problems inherent with using a Windows PC clock for time-stamping of data.

Note on Use of Concurrent Mag/EM61: The simultaneous acquisition of magnetometer and EM61 data is facilitated by use of the Man-Portable Interleaving (MPI) box developed under project MM-0414. This hardware acquires low-noise magnetometer data by interleaving the magnetometer data between the EM61 pulses (sampling the magnetometer only after the EM61's 75Hz pulse, and all of the secondary field it generates, have rung down). While no new development was performed (other than minor changes to its internal software, the MPI box from MM-0414 was used as internal COTS), the G-882 magnetometer was special-ordered from Geometrics with a Larmor output, as the technical approach of interleaving requires the MPI box to have access to the magnetometer's Larmor signal. Other than that, both the magnetometer and the EM61 submersible coil are COTS items. The magnetometer sensor head is located five feet from the outer edge of the EM61 coil. This is a foot further than was used in MM-0414. The extra foot allows for the physical form factor of the G-882 magnetometer.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The USEMS technology has three primary advantages over other marine metal detectors. The first is that, because the sensors are affixed via a rigid boom instead of towed with a cable, USEMS has the ability to position a magnetometer and an EM coil close to the bottom in relatively shallow constricted areas. The second advantage of the technology is that, because the boom is rigid and all of its rotational degrees of freedom are instrumented, the positional uncertainty should be substantially less than with a cable-towed system. The third advantage of the technology is that both magnetometer and pulsed EM data are acquired in a single survey pass, allowing for detection of non-ferrous or low-ferrous objects.

Limitations of the technology are that USEMS' six-meter boom limits its survey depth to about 3.6 meters, and that the EM61's one-meter swath width requires multiple closely-spaced survey lines for full coverage. Experience at the Plum Tree Island demonstration shows that, because USEMS uses a small (17') boat, the ability to follow one-meter planned traverses is influenced by wind, wave, and wake, though pilot experience can significantly minimize this limitation.

3 PERFORMANCE OBJECTIVES

The objectives of the demonstration were to verify:

- The hydrodynamic stability of USEMS' submerged towfish
- The ability of USEMS to maintain a constant height above bottom
- The accuracy of the geodetically combined sensor and positioning data
- The ability of USEMS to cover an area with data tracks
- The general ease of operation of the system

These heuristic objectives resulted in the following table.

Table 1: Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria	Criteria Met?
Quantitative Performance Objectives				
Towfish is hydrodynamically stable	Absence of periodic motion creating deviation from linear towed motion	• Dynamic survey data	Amplitude of periodic horizontal and vertical motion < 20cm	Horizontal: Yes, <~5cm Vertical in deeper water: Yes , <~5cm Vertical in shallow water: No, ~50cm, probably due to prop wash)
System can maintain a constant height above bottom	Deviations from desired height above bottom	• Dynamic survey data	Standard deviation < 50cm	Yes, standard deviation <19cm
Geophysical measurements are geodetically accurate	Average error and standard deviation in northing and easting for ground truth items	• Geodetic coordinates of emplaced test plot objects • Dynamic survey data over test plot objects • Analysis of survey data	ΔN and ΔE < 50cm σN and σE < 1 m	Yes, ΔN and ΔE < 37cm σN and σE < 19cm
USEMS system noise is similar to MSEMS system noise	Standard deviation of noise	• Dynamic survey data without targets present	σ USEMS noise ≤ 1.2 times σ MSEMS.	Mag: Yes, 0.06 EM61: No, 18.5
Track guidance system is usable for area surveys	Oasis missed area	• Dynamic survey data	< 5% missed area	No, 21%, but this is attributed mostly to lack of pilot experience. The track guidance system functioned to specification.
Qualitative Performance Objectives				
System is operable by two-man crew	Operator observations	• Time spent setting up the system and collecting dynamic survey data	All required functions can be executed by boat pilot and fish operator	Yes
Equipment layout and information allows operators to do their jobs	Operator observations	• Time spent collecting dynamic survey data	Boat pilot and fish operator are presented with information sufficient for them to perform their jobs	Yes, but can be further improved with guidance computer

3.1 OBJECTIVE: TOWFISH IS HYDRODYNAMICALLY STABLE

Although the towfish's hydrodynamic stability was tuned and tested prior to the Plum Tree Island demonstration, the pre-demonstration testing occurred in fresh lake water without currents or tidal changes.

3.1.1 Metric

The metric is the presence of periodic deviation from linear motion, and the amplitude of that periodic deviation.

3.1.2 Data Requirements

Fish height data were extracted from survey data over the shallow and deep test plots, as well as traverse data acquired off Plum Tree Island.

3.1.3 Whether Success Criteria Were Met

The success criteria were met horizontally, and were met vertically on the deep test plot, but were not met vertically on the shallow test plot.

3.2 OBJECTIVE: SYSTEM CAN MAINTAIN A CONSTANT HEIGHT ABOVE BOTTOM

The height of the USEMS towfish above the bottom is manually controlled via a joystick by an operator watching a computer screen showing the fish's altitude and depth in the water column and the depth of the approaching water column. Like the system's hydrodynamic stability, the ability of the system to maintain a constant height above bottom was tested and tuned in fresh water prior to the Plum Tree Island demonstration.

3.2.1 Metric

The metric was the average height above bottom and the standard deviation of the height during traverses, excluding turnarounds.

3.2.2 Data Requirements

The data were extracted from the survey data acquired over the shallow water test site, and the deep water test site.

3.2.3 Whether Success Criteria Were Met

The success criteria were met.

3.3 OBJECTIVE: GEOPHYSICAL SURVEY MEASUREMENTS ARE GEODETICALLY ACCURATE

USEMS' technical approach employs a magnetometer and EM61 in a towfish located at the end of a rigid six-meter kinematic boom whose pivot points are instrumented. This is intended to eliminate many of the positional uncertainties typically associated with cable-towed systems. The calculation of the sensor locations is a function of GPS position, boat heading, boat pitch and yaw, boom pitch yaw and roll, the yaw of the bridle holding the towfish to the boom, and the roll and pitch of the towfish. The basic functionality of this calculation was verified statically, and was tested and tuned in dynamic testing in a lake local to Waltham MA, but the Plum Tree Island demonstration was the first chance to test this in water that was not glass-smooth.

3.3.1 Metric

The metric was the average error and standard deviations in the geodetic versus emplaced target locations.

3.3.2 Data Requirements

These data were extracted from survey data over the shallow water test plot.

3.3.3 Whether Success Criteria Were Met

The success criteria were met.

3.4 OBJECTIVE: USEMS NOISE IS SIMILAR TO MSEMS NOISE

USEMS' employs an EM61 MKII and a total field magnetometer. Both of these sensors individually have their own noise envelopes. USEMS' interleaving electronics allows the two sensors to operate concurrently.

3.4.1 Metric

The metric was the standard deviation of the amplitude of the magnetometer and EM61 data in an object-free area.

3.4.2 Data Requirements

The data were extracted from survey data over the test plot in areas bereft of targets and clutter.

3.4.3 Whether Success Criteria Were Met

The success criteria for noise was met for the magnetometer, but was not met for the EM61.

3.5 OBJECTIVE: TRACK GUIDANCE SYSTEM IS USABLE FOR AREA SURVEYS

The design of USEMS includes display of planned traverses and real-time updates in MagLog at the fish operator's station, and a COTS Trimble EZ Guide lightbar mounted directly in the boat operator's field of vision at the boat operator's station. Like other lightbars from the agricultural product space, the EZ Guide prompts the operator to determine a reference line, creates tracks parallel to it, and visually guides the operator in performing parallel swathing with a bright linear LED display with green on-center LEDs and red off-center LEDs mounted directly in the operator's field of view. The EZ Guide also displays the planned and actual tracks using a perspective-mapped view on a small dedicated screen also mounted directly in the operator's field of view. Agricultural products such as the EZ Guide require the operator to actually drive the reference line in order to set the beginning and end points, but we developed a simple piece of software that feeds the endpoints of the desired reference line into the EZ Guide by converting them to simulated NMEA GPS strings. We successfully used the lightbar in this fashion at the Plum Tree Island demonstration, configuring it so the reference line was the center line of the shallow test plot (or the deep test plot). In addition to the EZ Guide, MagLog displays a birds-eye map of both pre-planned tracks and real-time GPS updates, but does not offer an off-track indicator.

3.5.1 Metric

The metric was the missed area measurement provided by Geosoft Oasis Montaj.

3.5.2 Data Requirements

These data were extracted from GPS readings from the survey data over the shallow test plot.

3.5.3 Whether Success Criteria Were Met

The success criteria were not met.

3.6 OBJECTIVE: SYSTEM IS OPERABLE BY TWO-MAN CREW

USEMS was designed to be operable by a two-man crew consisting of a boat operator and a fish operator. Demonstration surveys, however, typically utilize a crew including the principal investigator and principal engineers to troubleshoot problems in the field. We had a crew of four. Kelly Enriquez from USACE (the PI) oversaw general operations. Robert Siegel from SAIC (the co-PI) was fish operator for the entire survey. There were three boat operators: Dr. Roy Richard (USEMS' mechanical designer); John Morris (a marine survey engineer from SAIC's Newport office), and Davis Sanford (from Brooke Ocean Technology) who swapped for John Morris for one week of the survey.

3.6.1 Metric

This was a qualitative objective. The metric was the observations of the crew.

3.6.2 Data Requirements

Notes were kept during field surveys of which essential activities were performed by which crew members.

3.6.3 Whether Success Criteria Were Met

The success criteria were met.

3.7 OBJECTIVE: OPERATORS ARE PRESENTED WITH SUFFICIENT INFORMATION TO DO THEIR JOBS

USEMS was designed to be operable by a two-man crew consisting of a boat operator and a fish operator. The boat operator needs to pilot the boat to the designated survey area and, once there, survey pre-planned lines. The fish operator needs to monitor the geophysical and positioning sensors and keep the fish at the desired height above bottom. Both operators need to pay attention to changing bottom conditions. The boat operator is presented with a commercial bottom profiler that also has general navigation and chart plotting capabilities, and a commercial lightbar for track guidance. The fish operator is watching a Windows computer screen showing data in MagLog. Both of these displays can be customized and configured to a high degree.

3.7.1 Metric

This was a qualitative objective. The metric was the observations of the boat and fish operators.

3.7.2 Data Requirements

Notes were kept during field surveys of the boat and fish operators' observations. Desired changes to equipment placement, and information displayed in windows and menus, were noted. Whenever possible, these changes were made in the field.

3.7.3 Whether Success Criteria Were Met

The success criteria were met.

4 SITE DESCRIPTION

4.1 SITE SELECTION

The demonstration was conducted at Plum Tree Island, near the former Plum Tree Island bombing range in Virginia. The site was selected because it met the criteria in the white paper submitted last year to the Program Office (“MM-0733 “Requirements for a Successful Demonstration”). The Plum Tree Island site was sufficiently shallow to use the system; it was close to shore with easy access; it had a relatively flat sandy bottom; and it was of interest to USACE because it is an active RI/FS site. The site’s location is shown on the maps in the figures below.

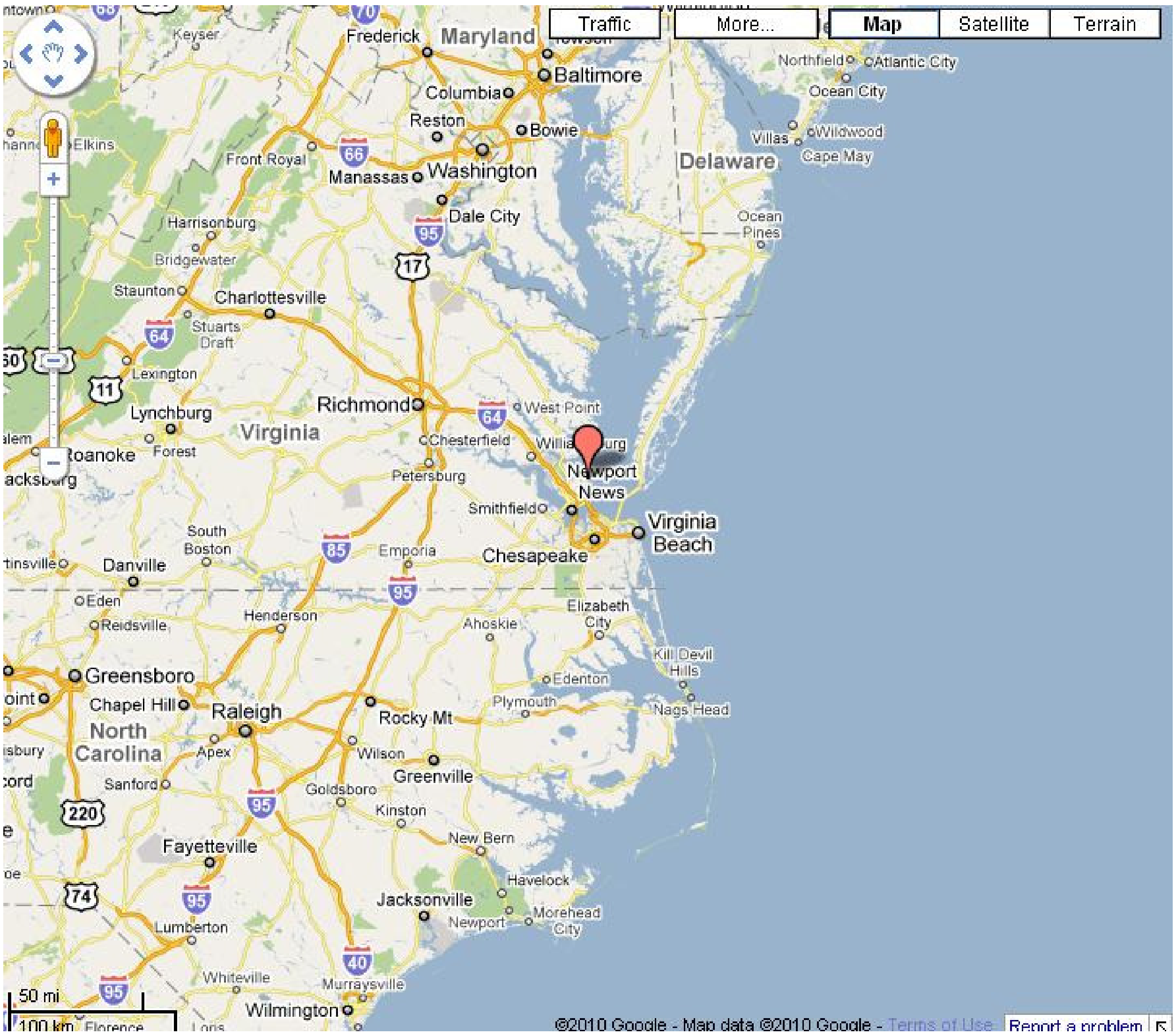

Figure 10: Location of Plum Tree Island site (zoomed out)

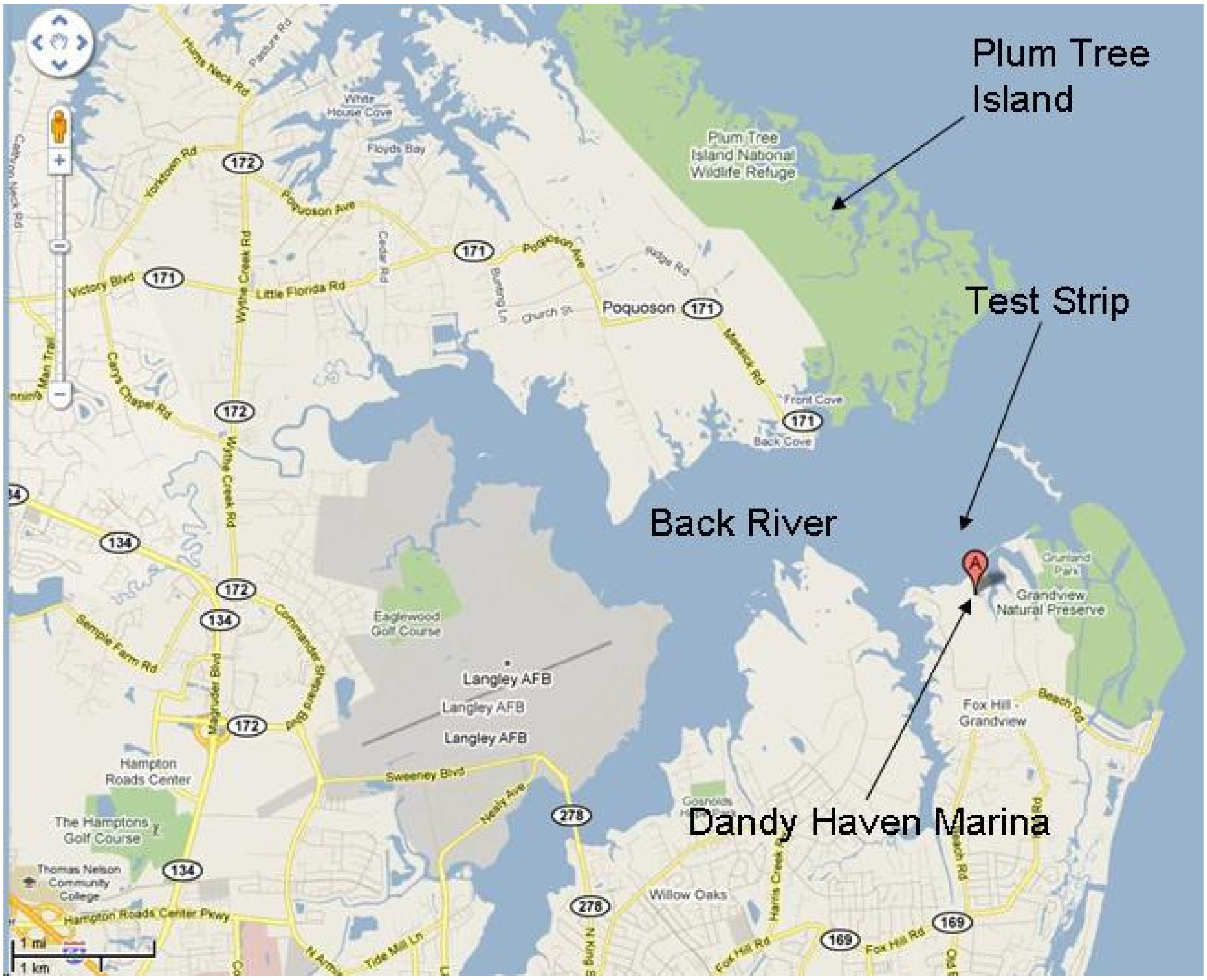

Figure 11: Location of Plum Tree Island site (zoomed in)

4.2 SITE HISTORY

Plum Tree Island is situated on the southwestern corner of the Chesapeake Bay near the City of Poquoson, Virginia. It was owned by the Department of Defense from 1917-1972 and was used for aerial bombardment and gunnery practice into the late 1950's. In 1972 it was transferred to the United States Fish and Wildlife Service. Today Plum Tree Island is one of four National Wildlife Refuges in the Eastern Virginia Rivers National Wildlife Refuge Complex.

4.3 SITE GEOLOGY

The site has a sandy bottom. The geology was benign to both the magnetometer and the EM61.

4.4 MUNITIONS CONTAMINATION

There is a high probability of the presence of munitions and explosives of concern (MEC) on the eastern sections of Plum Tree Island. During a previous survey, on-shore cleanup efforts, guided by the results of geophysical transects and grids, identified a wide variety of MEC and munitions debris (MD), including small arms, 50 pound bombs, five inch rockets and Jet Assisted Take Off (JATO) bottles. A shoreline sweep for surface items also uncovered 263 JATO bottles, along with occasional bomb and rocket parts. Additionally, an underwater EM transect survey conducted by USACE in 2009 resulted in the likely presence of buried metallic objects, with the largest concentration off the southeast corner of the island.

5 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The conceptual experimental design was to identify a flat, shallow (chest-high), metallically uncluttered area, construct a test plot approximately 10m x 100m of pipes of four sizes simulating four ordnance types in their most and least favorable orientations, emplace the objects at low tide without the use of divers, shoot in the locations carefully with GPS, then survey the test plot with USEMS at low tide and at high tide, at several different heights above bottom, and at several different survey speeds to allow us to evaluate the system's geolocation accuracy in varied orientations by comparing the calculated and actual object locations using the changing boom orientation recorded by the system's positioning sensors. The fact that the test plot had cross-track extent (as opposed to a strictly linear test strip) made the survey require multiple passes, allowing us to evaluate the system's ability to cover an area with parallel data tracks.

The conceptual experimental design included identifying a deeper section of water and testing the system's bottom-following ability, but without a second deeper emplaced test plot, as the use of divers would substantially impact the cost of the demonstration. We planned to emplace several objects in the deep test plot by maneuvering the boat within a meter of the planned location and dropping them over the side.

5.2 SITE PREPARATION

Other than emplacement of the test plot (described in section 5.5) and a background survey to ensure the absence of metallic clutter, there was no site preparation.

5.3 SYSTEM SPECIFICATION

A general system description was included above in section 2.1. Sampling rates and other relevant parameters are listed below.

5.3.1 Pulsed Induction Sensor

The EM61 MKII pulsed induction electronics are located topside and connected to a single 1 x ½ meter EM61-S (submersible) coil in the towfish, with the long axis of the coil oriented across the width of the towfish. The electronics are employed in their COTS mode using time gate values of 256, 406, 706, and 1306 usec. Data acquisition is controlled by MagLog "soft-triggering" the EM61. EM61 data are acquired at a 10Hz rate.

5.3.2 Total Field Magnetometer

Data from the Geometrics G882 magnetometer are acquired, interleaved between EM61 pulses using the interleaving electronics from project MM-0414. This allows the Larmor signal from the magnetometer to be sampled every 13.3 ms, for a 5ms duration, just before the next EM61 transmit pulse begins. The period counter in the interleaving hardware converts the frequency-based Larmor signal to nanotesla and outputs it in an ASCII comma-delimited format. Because sampling of the magnetometer data is interleaved between EM61 pulses, the magnetometer sampling rate is the same as the EM61 internal pulse repetition rate, namely 75Hz. The ASCII data stream is then read and stored in MagLog. The magnetometer and the EM61 coil are both located in the towfish. Prior work on MM-0414 determined that, even with interleaving, a four-foot coil-to-magnetometer separation is necessary to ensure that the Larmor signal hasn't gone out of range from the EM pulse. USEMS employs a safety factor; the magnetometer's sensor head is located five feet behind the edge of the EM61-S coil.

5.3.3 GPS

A Trimble MS860II GPS receiver is installed in the boat, with antennas mounted at the bow and stern along the centerline that intersects with the pivot point of the boom. The GPS is operated in Real Time Kinematic (RTK) mode. To eliminate the problem of where to set up a base station for a marine survey, we employed a subscription-based RTK correction service implemented via a cellular modem over a Real Time Network (RTN). A NMEA GGK string containing the time and the location of the stern antenna are output at 10Hz and recorded by MagLog. A second string, the NMEA AVR string containing the heading, are output at 10Hz and recorded by MagLog. Note that the Trimble MS860II is designed to output heading using a "moving base" configuration where the heading of the bow antenna is relative to the location of the stern antenna, thus making the heading measurement insensitive to momentary loss of base station corrections.

5.3.4 Boat Inclinometer

The roll and pitch of the boat are measured using a gravity-referenced inclinometer outputting at a 10Hz rate and recorded by MagLog.

5.3.5 Boom Rotary Position Sensors

The yaw, pitch, and roll of the pivot point at the topside of the boom are measured using rotary positioning sensors integrated directly into the pivot. The sensors are laser-sighted so that they read zero when the boom is straight behind the two GPS antennas and is parallel with the mounting surface for the boat inclinometer. The RPS are read by a programmable logic controller (PLC) which outputs data to MagLog at a 10Hz rate.

5.3.6 Bridle Yaw Rotary Position Sensor

A fourth RPS is mounted where the bridle is attached to the wet end of the boom. It is laser-sighted to read zero when the bridle is straight behind the boom. This RPS is also read by the programmable logic controller (PLC) that outputs to MagLog at a 10Hz rate.

5.3.7 Fish Inclinometer

The roll and pitch of the towfish are measured using a gravity-referenced inclinometer outputting at a 10Hz rate and recorded by MagLog.

5.3.8 Fish Depth and Altitude

Along with the magnetometer itself, the COTS Geometrics G882 contains a depth transducer and an altitude sonar. These are output (along with non-interleaved magnetometer data) at 10Hz and recorded by MagLog. The fish altitude is watched by the fish operator who uses a joystick to control the hydraulically-actuated dive planes to try to keep the fish at a constant height off the bottom.

5.3.9 Boat Water Depth Transducer

A depth transducer is mounted on the boat, and outputs the NMEA DBT (depth below transducer) string at 1 Hz. These data are used by the fish operator to alert him of the water depth that the boat is entering. Although these data are recorded by MagLog, they are not used in the geolocation calculation.

5.4 CALIBRATION ACTIVITIES

There were no calibration activities per se.

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5.5 DATA COLLECTION

5.5.1 Scale

There was substantial advantage in locating the test plot in the Back River area (as opposed to offshore of Plum Tree Island), as the Back River area was considerably more sheltered from wave and wind than Plum Tree Island, and was only ten minutes from the marina where the equipment was based, whereas Plum Tree Island was 45 minutes away. We went out with a local expert (the owner of the marina where we based the equipment) to have him assist us in locating an appropriate area in the Back River for the shallow water test site. The area he helped us select, however, turned out to be too deep to allow us to emplace objects on the bottom (that is, an operator could not stand with his head out of the water, hold a GPS on a pole, and sight a bubble level). Other broad shallow areas proved in fact to be too shallow for the boat to navigate at anything other than dead high tide. The presence of buoys and crab traps, and the proximity to the main deep channel, further restricted the choice of area. Bathymetric maps proved inaccurate at the small-scale level of detail required for test plot specification. We used the depth sensor in the boat to identify a small plateau that was sufficiently shallow to allow emplacement of the test plot at low tide and was long and wide enough to host the test plot. Unfortunately, though, the water depth of the area was only chest-high at high tide, and thus did not allow for the testing USEMS for varying height above bottom or tidal height.

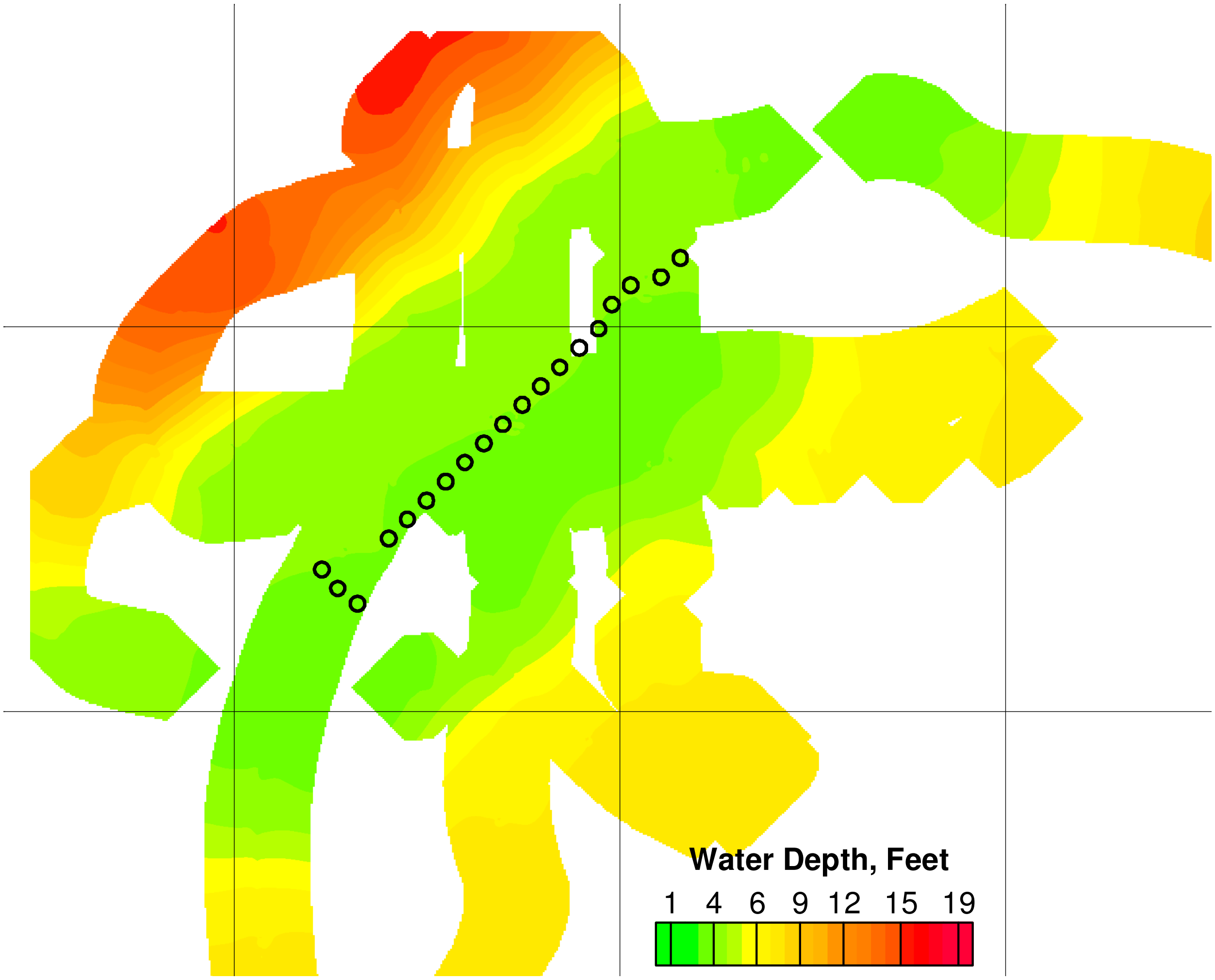

Figure 12: Bathymetry data used to identify and lay out shallow water test plot. Large squares are 100 meters.

The sections of standard Schedule 40 steel pipe used for the test plot objects are listed in the table below. These pipe objects are shown next to the objects they simulate in the figure below.

Table 2: Standard pipe thicknesses

Common Name	Outside Diameter (in)	Wall Thickness (in)	Length (in)
4"	4.5	0.24	18
3"	3.5	0.22	18
2"	2.375	0.15	12
1.5"	1.875	0.15	12

Figure 13: Pipe simulants for 60mm, 81mm, 2.75", and 105mm items

The actual objects we emplaced in the shallow water test plot, their planned down-track and cross-track locations, and their coordinates are shown in the table below. Coordinates are in WGS84 UTM zone 18N, meters. All objects were emplaced by walking to the planned location using an RTK GPS, placing the object at that location, then recording the location of the center of the object with the GPS. The first object is a pair of six-meter long pipes laid end to end to act as a start-of-track fiducial. The objects along the center line are 4", 3", 2", and 1.5" pipes in their most-favorable (vertical) and least favorable (horizontal cross-track and horizontal down-track) orientations, for a total of twelve on-center objects. Four additional objects are located off-center (two 2" and two 1.5" pipes). The down-track separation of all other objects is seven meters.

Table 3: Shallow water test plot objects

Object	Description	Location	x	y
0	Two 1.5" pipes 20' long laid end to end	across		
1	4" pipe 18" long vertical	centered	383940.09	4107045.03
2	4" pipe 18" long horizontal cross-track	centered	383944.95	4107049.99
3	4" pipe 18" long horizontal down-track	centered	383949.88	4107054.84
4	3" pipe 18" long vertical	centered	383954.89	4107059.80
5	3" pipe 18" long horizontal cross-track	centered	383959.82	4107064.77
6	3" pipe 18" long horizontal down-track	centered	383964.74	4107069.68
7	2" pipe 12" long vertical	centered	383969.67	4107074.62
8	2" pipe 12" long horizontal cross-track	centered	383974.68	4107079.66
9	2" pipe 12" long horizontal down-track	centered	383979.53	4107084.52
10	1.5" pipe 12" long vertical	centered	383984.42	4107089.43
11	1.5" pipe 12" long horizontal cross-track	centered	383989.48	4107094.46
12	1.5" pipe 12" long horizontal down-track	centered	383994.50	4107099.40
13	3" pipe 12" long vertical	2m left	383997.90	4107105.71
14	3" pipe 12" long horizontal cross-track	2m left	384002.83	4107110.69
15	2" pipe 12" long vertical	2m right	384010.63	4107112.78
16	2" pipe 12" long horizontal cross-track	2m right	384015.63	4107117.79

In addition to the shallow water test plot, a deeper water test plot was used. This consisted of four objects (two 4” and two 3” pipes) placed approximately 10 meters apart in water approximately two meters deep along a line aligned north-south. Because the water was too deep for a person to stand (either to emplace the objects or measure their placement), emplacement was performed by anchoring the boat upwind of each location, letting out line to float the boat to the approximate northing location, and using a small powered skiff to swing the boat laterally to the approximate easting location. When northing and easting were within a meter of the desired location, the object was dropped. Because the objects needed to be retrieved, a rope with a buoy was tied to each object. However, because the rope and buoy could snag on the towfish or propeller, a scheme was devised to weigh down the lines with non-metallic weights (flowerpots) and stretch the lines laterally westward so the buoys would float up about ten meters west of the objects. The planned locations of the objects are in the table below. Despite the J-shaped lines, the line to one object was snagged on the first day of deep testing, and the object was dragged outside the test plot; that object has been removed from the table.

Table 4: Deep water test plot objects

object	description	x	y
1	4" pipe 18" long horizontal	383905	4106850
2	4" pipe 18" long horizontal	383905	4106860
3	3" pipe 18" long horizontal	383905	4106880

5.5.2 Sample Density:

The cross-track line spacing was 1 meter. We had planned to acquire data at boat speeds of 1 meter per second, 2 meters per second, and 3 meters per second, which, coupled with the EM61’s 10Hz output rate, yields down-track EM61 data densities of 10cm, 20cm, and 30cm respectively, but because the shallow water test site was shallower than planned, and because higher speeds had the effect of driving the towfish into the bottom, speed was not used as an independently adjustable parameter in a test matrix as planned. The boat driver drove the boat at a speed high enough to mitigate drift from wind, wave, and wake, but low enough not to drive the fish into the bottom. The average speed on the shallow test plot was approximately 1.2 meters per second, resulting in a down-track EM61 data spacing of approximately 12 cm, and a down-track magnetometer spacing of approximately 1.6cm.

5.5.3 Quality Checks

All geophysical sensor and positioning sensor data were displayed on the MagLog computer and examined in real time by the fish operator. Visual and audible alarms were employed to alert the fish operator if data output ceased from any sensor, or was outside an acceptable range. In this way, MagLog alerted the operator if the GPS lost its link with the base station, or collected data that were not of RTK fixed integer quality, or if the GPS clock board malfunctioned or lost its timing base.

5.5.4 Data Summary

The data reside at SAIC in Waltham MA, on the server and archived to DVD. The data also reside at USACE Huntsville. Data exist:

- In their raw form of MagLog-stored time-stamped ASCII files (described in section 6.6)
- As geolocated ASCII files
- As Oasis databases

A table of available data files, their survey area (shallow water test site, deep water test site, or "area files" acquired as traverses off Plum Tree Island) and their water depth, target fish height, and average fish height (units in meters), is shown below.

Table 5: Metadata for acquired data files (meters)

	wd mean	height target	height mean
pti-09-17-2010 shallow1a	0.95	0.5	0.39
pti-09-19-2010 shallow2	0.99	0.5	0.32
pti-09-20-2010 shallow5	1.16	0.5	0.44
pti-09-21-2010 shallow7	1.07	0.5	0.41
pti-09-23-2010 shallow8	0.9	0.5	0.32
pti-09-23-2010 shallow9	0.98	0.5	0.36
pti-09-23-2010 shallow10	0.96	0.5	0.31
pti-09-23-2010 shallow11	0.87	0.5	0.27
pti-09-18-2010 deep2	2.26	1.5	1.48
pti-09-18-2010 deep3	2.26	1.0	1.02
pti-09-19-2010 deep7	2.31	1.0	1.03
pti-09-19-2010 deep8	2.25	0.5	0.49
pti-09-20-2010 deep10	2.35	1.5	1.51
pti-09-21-2020 deep12	2.31	1.5	1.54
pti-09-21-2010 deep13	2.2	1.0	0.98
pti-09-21-2010 deep14	2.16	0.5	0.5
pti-09-23-2010 deep16	1.85	0.5	0.54
pti-09-23-2010 deep17	1.82	0.5	0.46
pti-09-24-2010 deep18	2.56	1.5	1.4
pti-09-24-2010 deep19	2.57	1.0	1.02
pti-09-24-2010 deep20	2.57	0.5	0.49
pti-09-24-2010 deep21	2.57	0.5	0.49
pti-09-24-2010 deep22	2.54	1.0	0.99
pti-09-21-2010 pti_area1	1.17	0.5	0.44
pti-09-22-2010 pti_area1_contd	1.54	0.5	0.71
pti-09-22-2010 pti_area3	1.98	0.5	0.63
pti-09-22-2010 pti_area4	1.73	0.5	0.66
pti-09-22-2010 pti_area5	1.42	0.5	0.56

5.6 VALIDATION

Not applicable.

6 DATA ANALYSIS AND PRODUCTS

The basic data flow of USEMS has the magnetometer, EM61, GPS, rotary positioning sensor, inclinometer, altimeter and depth sensor data streaming into MagLog, time-stamped with GPS time, and stored in files. All raw files are ASCII except the EM61 data file. All files are then read by a piece of software ("usemsproc") which time-correlates the geophysical and positioning data, performs the geodetic calculation, notch-filters the magnetometer data, background-levels the magnetometer and EM61 data, and writes out ASCII leveled magnetometer and EM61 data files that are then read into Oasis. This data flow is depicted in the figure below.

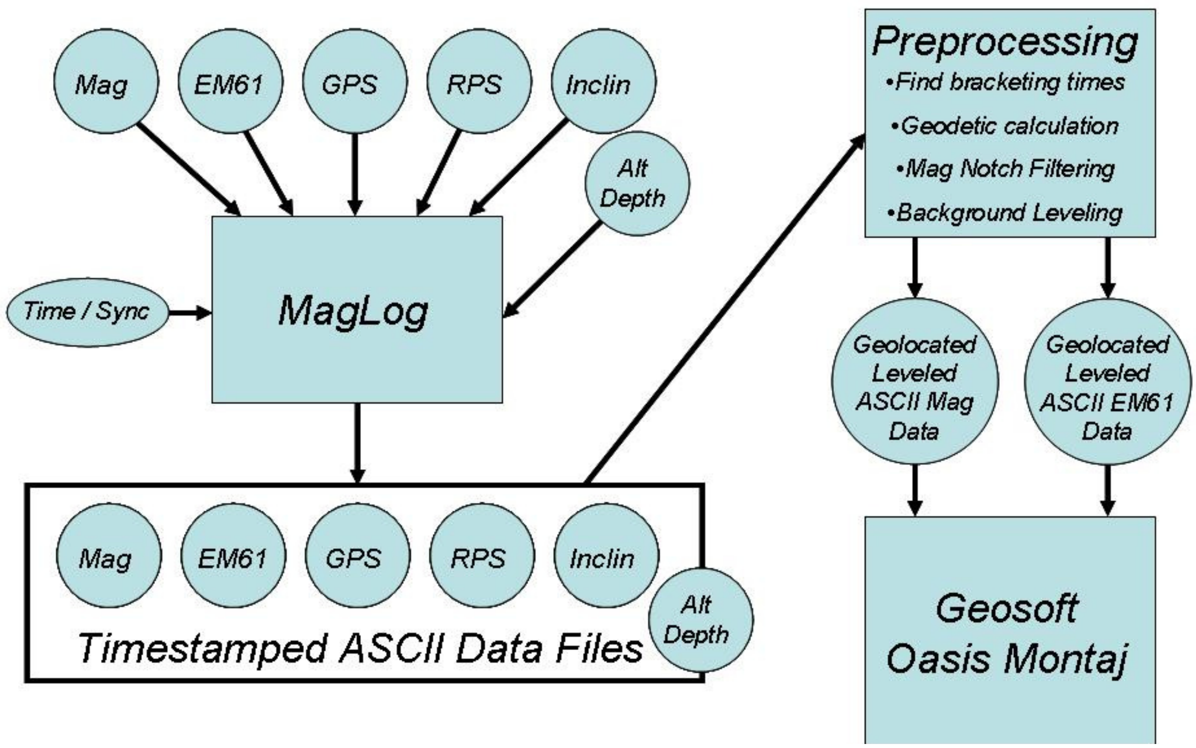

Figure 14: USEMS data flow

6.1 PREPROCESSING

All preprocessing occurs in the program "usemsproc."

Notch Filter: Because USEMS acquires concurrent mag and EM61 data, the magnetometer sampling occurs at the EM61's 75Hz pulse repetition rate. At 75 Hz, the ubiquitous 60 Hz hum from ambient electrical activity aliases flawlessly at 15 Hz. A de-spiking median filter is first applied to the time-series magnetometer data on each line to remove spurious values. A notch filter is then applied to the magnetometer data to remove the 15 Hz aliased signal.

Background Leveling: A de-median filter with a 6-second window is applied to both the magnetometer data and the EM61 data to determine a background value. This value is then subtracted from the data, resulting in dynamic background leveling. This removes instrument drift from the EM61 data. It also removes the effect of geology and any small effect of the signature from the boat or its motor from the magnetometer data.

Forward Kinematic Model: All data acquired by MagLog are time-stamped using the GPS time (the MagLog computer contains a GPS clock card). The magnetometer and EM sensor updates are read. For each sensor update, the time is examined, the closest set of bracketing times of the positioning sensors (GPS, RPS, and inclinometer values) are found, and a new positioning value is interpolated across the time gap. A forward kinematic model is then employed that factors in the appropriately interpolated positioning values for the position, roll, and pitch of the back of the boat, the roll, pitch, and yaw of the boat, the angles of the boom, and the roll, pitch, and yaw of the fish.

6.2 TARGET SELECTION FOR DETECTION

Not applicable.

6.3 PARAMETER ESTIMATES

Not applicable.

6.4 CLASSIFIER AND TRAINING

Not applicable.

6.5 DATA PRODUCTS

The data in their raw form are stored in eight files created by MagLog. These are space-delimited files for:

- EM61 MKII
- Magnetometer
- GPS stern position, time, and heading
- Four rotary positioning sensor values (boom yaw, pitch, and roll, and bridle yaw)
- Boat inclinometer pitch and roll
- Towfish inclinometer pitch and roll
- Output from G882 (non-interleaved magnetometer, fish depth, fish altitude)
- Boat depth transducer

Each entry in each file is time-stamped by MagLog using the time derived from the computer's GPS clock card. The above files are ASCII except for the EM61 MKII file.

6.5.1 EM61 MKII DATA FILE

The EM61 MKII data file stores the EM61's standard binary 16-byte message. As such, a sample is non-ASCII and non-printable. It's contents are the 16-byte binary message, followed by four blanks, followed by the 8-character date, followed by the 12-character time in HH:MM:SS.SS format.

6.5.2 MAGNETOMETER DATA FILE

A sample line of the interleaved magnetometer file is:

$M, **50556.1**, 128 01/11/10 **15:03:23.578**

The second field is magnetometer value in nanotesla, and the last is time in HH:MM:SS.SSS format. These relevant fields have been bolded.

6.5.3 GPS DATA FILE

The GPS file contains both the NMEA-standard GGK string containing time, latitude, longitude, and fix quality, and the AVR string containing heading (yaw). Both of these strings are well-documented on NMEA-related web sites. The time, latitude, longitude, fix quality, and yaw have been bolded. Two sample lines of the GPS file is:

$PTNL,GGK, **172814.00**, 071296, **3723.46587704** ,N, **12202.26957864**, W, **3**, 06,1.7,EHT-6.777,M*48

$PTNL,AVR, **172814.00**,**+149.4688**,Yaw,+0.0134,Tilt,,,60.191,3,2.5,6*00

6.5.4 RPS DATA FILE

A sample line of the Rotary Positioning Sensor data file is:

$PLC,**1786, 2528, 2528, 2528, 00** 01/06/10 **12:45:39.406**

The second field is the boom pitch, the third field is the boom yaw, the third field is the boom roll, the fourth field is the bridle yaw, and the last is time in HH:MM:SS.SSS format. These relevant fields have been bolded. The four RPS values are PLC values varying from 0 to 4000, and correspond to a range from -60 to 60 degrees. They are converted to degrees as follows:

```
#define RPS_RANGE 60.0
rpsAngle = (2*RPS_RANGE*((double)rpsVal - 4000.0)/4000.0) + RPS_RANGE;
```

6.5.5 INCLINOMETER DATA FILE

A sample line of the boat inclinometer file for the boat or the towfish is:

$ **0.0134**, **1.5245**, 12.94,N3197 01/11/10 **15:03:23.562**

The first field is roll in degrees, the second is pitch in degrees, and the last is time in HH:MM:SS.SSS format. These relevant fields have been bolded.

6.5.6 BOAT DEPTH TRANSDUCER DATA FILE

A sample line of the boat depth transducer data file is:

$SDDBT, **004.5, f**, 001.4,M,000.7,F*05 01/11/10 **15:03:23.562**

The second field is the water column depth, the third field is the units ("f" for feet), and the last is time in HH:MM:SS.SSS format. These relevant fields have been bolded.

6.5.7 G882 DATA FILE

A sample line of the G882 data file is:

$ 50561.634, 0549, **0110, 9915** 01/11/10 **15:16:46.328**

The first field is non-interleaved magnetometer value in nanotesla (note that this value is not used since it is extremely noisy; the interleaved magnetometer data are used instead), the third field is raw (un-calibrated) fish depth, the fourth field is the raw fish altitude, and the last is time in HH:MM:SS.SSS format. These relevant fields have been bolded. The raw values are calibrated via the following linear equations:

```
fishDepth = DEPTH_SCALE*rawDepth + DEPTH_BIAS;
fishAltitude = ALTITUDE_SCALE*rawAltitude + ALTITUDE_BIAS;
```

For our G882, Geometrics supplies the following calibration constants. "_SALT" constants were employed for the processing of the Plum Tree Island data.

```
#define ALTITUDE_SCALE        0.00315
#define ALTITUDE_BIAS         -0.50
#define DEPTH_SCALE_SALT      0.005874
#define DEPTH_SCALE_FRESH     0.005991
#define DEPTH_BIAS_SALT       -0.59
#define DEPTH_BIAS_FRESH      -0.60
```

6.6 OUTPUT DATA FILES

The forward kinematic model is implemented at a Windows command line utility that reads these eight files and outputs two files meant for import into Geosoft Oasis Montaj – a geodetically-registered magnetometer file and a geodetically-registered EM61 data file. For these files, the format is:

- Easting and Northing (X and Y) values in UTM meters
- Coil_number or Magnetometer number (always 1)
- Path_number (a line count)
- The time in HHMMSS.SSS format
- The sensor data. For magnetometer data, the sensor data are each a single reading in nanotesla. For the EM61 MkII data, the sensor data are the four standard EM61 time gates.

7 PERFORMANCE ASSESSMENT

7.1 Hydrodynamic Stability

The vertical motion of the fish in the water column is directly measured by the altimeter and the depth transducer that are integrated with the COTS Geometrics magnetometer in the fish. Additional measures of fish motion can be obtained by examination of the inclinometer in the fish, and the rotary position sensor (RPS) that measures the pitch of the boom. In very shallow water, the fish altimeter is quite noisy, but the fish depth transducer and boom RPS readings are very stable. To be certain that the depth, altitude, and boom RPS are registering true vertical motion of the fish in the water column and not simply wave height changes, we also examined the boat inclinometer and boat altimeter data and cross-checked these with operator notes of the sea state (e.g., calm or wavy).

We found that, on all data from the shallow water test site, there is a non-trivial amount of vertical oscillatory motion – approximately 40 to 50 cm peak-to-peak, with a period of approximately six seconds. This oscillatory motion is present in the fish depth transducer, the fish altimeter, the fish inclinometer, and the boom pitch RPS, and is not present in the boat water depth sensor or the boat inclinometer. This indicates that this particular motion is not an artifact of wave action. A sample plot showing the fish depth (red) and boom pitch (pink) from a representative traverse of the shallow test site is shown below. The boom pitch is measured as a negative angle when the boom is in the water, thus is goes to an increasingly negative value as the fish goes deeper. This is why the boom pitch and fish depth appear out of phase. Note that the major oscillation in the boom pitch data is correlated with the oscillation in the fish depth data – the oscillation is driving the fish and thus the end of the boom up and down in the water column. The smaller higher-frequency oscillation in the boom pitch data is likely due to minor wave-induced boat motion.

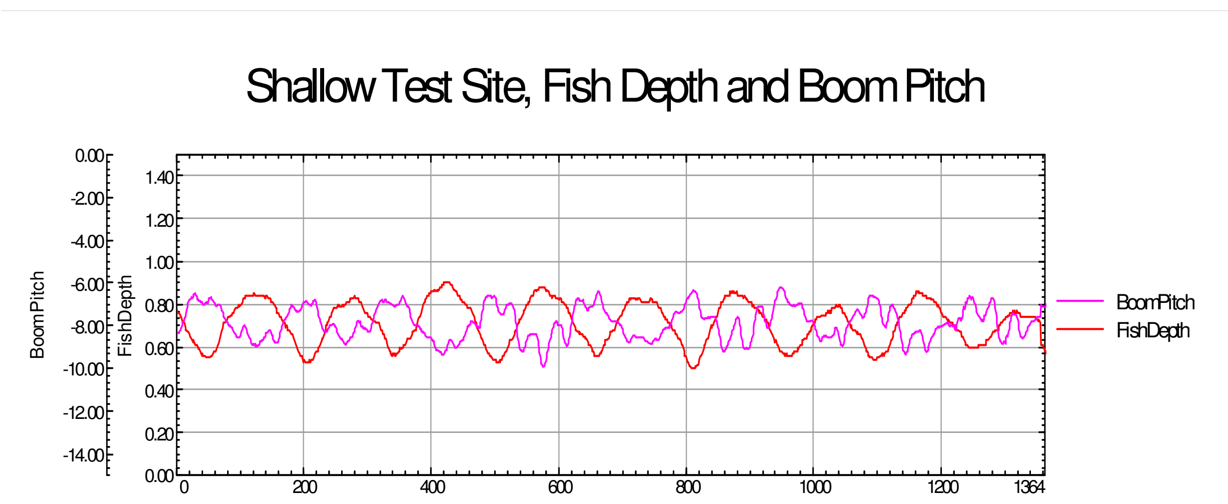

Figure 15: Example of periodic motion in one traverse of the shallow test site. Horizontal axis is fiducial number of 10Hz readings (approximately 135 seconds of data)

In the demonstration test plan, we said that the objective would be met if the amplitude of periodic motion was less than 20cm in both the vertical and horizontal directions. There is no evidence of periodic motion in the horizontal direction. However, the motion exceeds the criteria in the vertical direction. Thus, the success criteria were not met on the shallow test site.

However, this vertical periodic motion of the fish *is not present* in data from the deep water test site. In the figure below, fish depth and boom pitch data from one traverse of the deep test plot are plotted to the same scale as above (1.5m range on the fish depth, and 15 degree range on the boom pitch). Note that there is no visible oscillation in the red fish depth data. The small oscillation in the pink boom pitch data is likely due to wave-induced boat motion. These data are representative of all of the data from the deep test plot. Oscillations of the form plainly seen in the shallow water test data are not seen in any of the deep water test data, and thus we estimate that any vertical periodic motion in these deep data has an amplitude less than approximately 5cm.

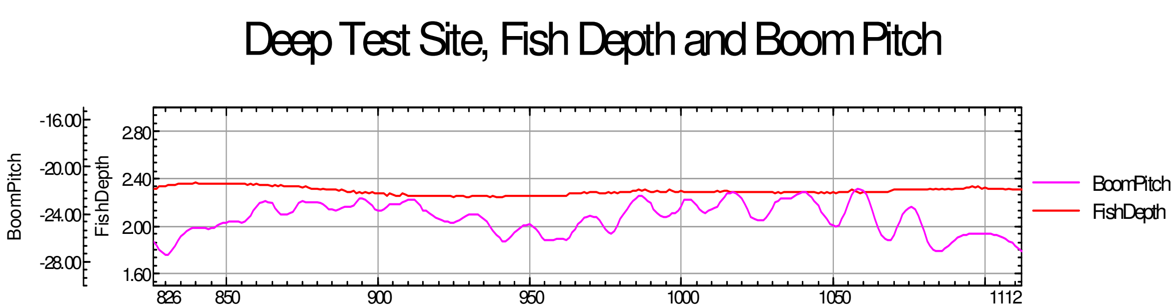

Figure 16: Example of lack of periodic motion in one traverse of the deep test site. Horizontal axis is fiducial number of 10Hz readings (approximately 30 seconds of data)

Note that difference in water depth between the shallow water test plot and the deep water test plot is not terribly great. While the surveys over the shallow test plot had the water depth vary as a function of tide from 0.87m to 1.2m, the surveys over the deep test plot had the water depth vary from 1.7m to 2.5m. Thus, the average additional water depth in the deep test plot is only approximately one meter greater than in the shallow water test plot.

In addition to the shallow and deep test plots, we also acquired traverse data off Plum Tree Island. Although most of the traverse data acquired off Plum Tree Island was in shallow water (approximately one meter), some was in deeper water, and the amount of periodic motion of the fish appears to vary with water depth. The deepest section was “area3” with water depth of approximately two meters, and as shown in the data below, the oscillation in fish depth appears to be less than 10cm peak-to-peak when the fish is at maximum depth. Note that the short discontinuities in the fish depth plot represent the system turning around or other interruptions in data collection.

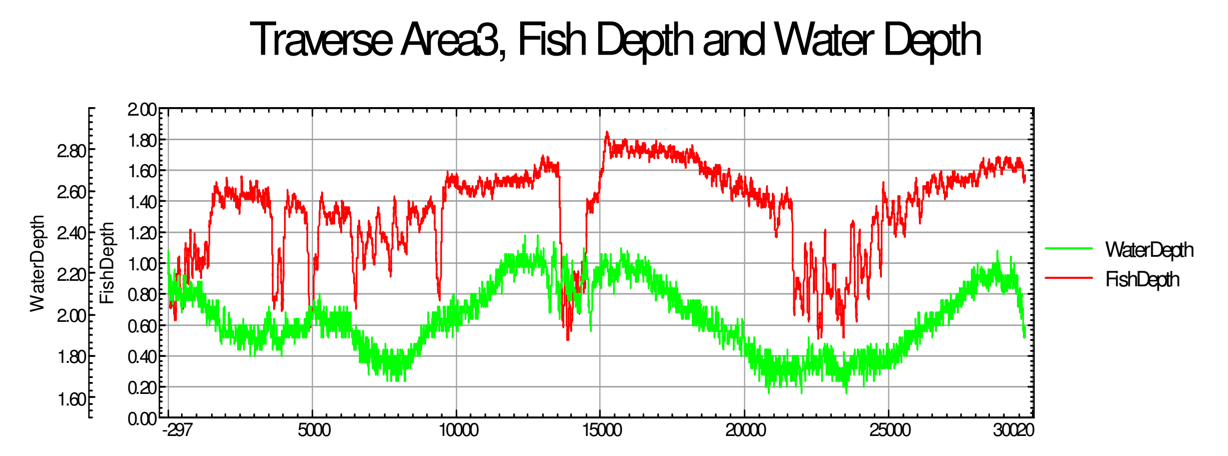

Figure 17: Example of periodic motion varying with depth in traverse data off Plum Tr3ee Island. Horizontal axis is fiducial number of 10 Hz readings

Because the oscillation only occurs in very shallow water, we hypothesize that the vertical motion may be caused by a shallow water effect such as the towfish operating in the boat's propeller wash.

Above we said that there is no evidence of horizontal oscillatory motion. Horizontal motion of the towfish relative to the end of the boom is not possible because the final design of USEMS includes a shear pin on the bridle pivot that keeps the axis of the towfish in line with the axis of the boom. Thus, although the system was designed with a rotary position sensor installed at the bridle pivot, this RPS reads a fixed value. Any horizontal oscillatory motion would involve pivoting of the entire boom in the horizontal plane, and there is no evidence of this in the line paths shown in section 7.3 below. Thus we estimate the magnitude of any horizontal oscillatory motion at < 5cm.

7.2 Maintaining a Constant Height Above Bottom

Plum Tree Island was a much shallower site than the lakes in which we performed most of the pre-demonstration testing. The demonstration test plan called for us to identify an appropriate area for a shallow test site (chest-high water at low tide, free of metallic clutter) and to emplace objects and survey the site at three different heights above bottom (0.5m, 1.0m, and 1.5m). However, it was difficult to find a flat area that was close to the marina where the equipment was based, was of the appropriate depth, and not cluttered with buoys or crab traps. After searching the area, the most appropriate spot we could find was water that was thigh-high at low tide and became chest-high at high tide. The shallowness of the test site, coupled with the fact that the towfish starts to dive to a depth of about .75 meters as soon as the boat pulls it forward, made it so that there was essentially no active depth control on the shallow water test site; we operated the system with the dive planes all the way up. Even in this configuration, the towfish hit the bottom of the shallow water test site when we tried surveying it when tide was not very near high.

In the demonstration test plan, we said that the objective will be met if the standard deviation of the height is less than 50cm. As we described above, for the runs in the shallow test plot, the height above bottom was not an independently adjustable variable (the shallow test plot was so shallow that we surveyed it near high tide and let the fish ride close to the surface). However, in the deep water test plot, the height *was* an independently adjustable variable. In the table below, we show, for each run over the shallow and deep test plot, the mean water depth, the target (desired) fish height, the min, max, mean, and standard deviation of the fish height, and the mean boat speed. All units are meters except for speed which in meters/second. We see that, for the deep test plot, the results are excellent – on all runs, the mean height is within 10cm of the desired height. The worst standard deviation is 19cm, and the average standard deviation is 12cm. Thus the success criteria were met.

Table 6: Fish height above bottom statistics (meters)

	wd mean	height target	height min	height max	height mean	height stdev	speed mean
shallow1a	0.95	0.5	0.03	0.74	0.39	0.15	1.00
shallow2	0.99	0.5	0.07	0.77	0.32	0.09	1.44
shallow5	1.16	0.5	0.13	0.71	0.44	0.01	1.55
shallow7	1.07	0.5	0.11	0.63	0.41	0.09	1.24
shallow8	0.9	0.5	0	0.57	0.32	0.1	1.14
shallow9	0.98	0.5	0.06	0.76	0.36	0.12	1.23
shallow10	0.96	0.5	0.07	0.54	0.31	0.11	1.31
shallow11	0.87	0.5	0.5	0.54	0.27	0.08	1.23
deep2	2.26	1.5	1.2	1.67	1.48	0.08	1.88
deep3	2.26	1.0	0.82	1.61	1.02	0.13	1.81
deep7	2.31	1.0	0.7	1.52	1.03	0.19	1.97
deep8	2.25	0.5	0.26	0.8	0.49	0.1	1.89
deep10	2.35	1.5	1.29	1.68	1.51	0.07	1.84
deep12	2.31	1.5	1.29	1.82	1.54	0.1	1.10
deep13	2.2	1.0	0.58	1.74	0.98	0.2	1.40
deep14	2.16	0.5	0.31	1.24	0.5	0.13	0.99
deep16	1.85	0.5	0.31	0.77	0.54	0.11	1.31
deep17	1.82	0.5	0.26	0.6	0.46	0.11	1.43
deep18	2.56	1.5	1.07	1.8	1.4	0.11	1.58
deep19	2.57	1.0	0.67	1.3	1.02	0.11	1.72
deep20	2.57	0.5	0.19	1.15	0.49	0.18	1.65
deep21	2.57	0.5	0.27	1.26	0.49	0.15	1.67
deep22	2.54	1.0	0.82	1.31	0.99	0.08	2.75
pti_area1	1.17	0.5	0	1.28	0.44	0.23	1.26
pti_area1_contd	1.54	0.5	0.12	1.67	0.71	0.32	1.47
pti_area3	1.98	0.5	0.16	1.7	0.63	0.26	1.61
pti_area4	1.73	0.5	0.17	1.62	0.66	0.21	1.44
pti_area5	1.42	0.5	0.27	1.02	0.56	0.13	1.51

7.3 Geodetically Accurate Survey Measurements

7.3.1 Analysis of Shallow Water Test Plot

In a terrestrial application, when acquiring data over a test strip, there is a high degree of control and repeatability in being able to pass the sensors directly over the objects; you see the flagged or marked object locations and simply maneuver the sensor(s) over them. However, this is not the case with an underwater test strip. Tall bicycle flags used to mark objects risk damaging the boat's propeller. Buoys and lines used to mark objects risk almost certain entanglement with the towed sensors. Because of this, the geolocation results carry the uncertainty of whether the sensor actually passed directly over the objects. In a system's first demonstration, it is difficult to separate the question "do the data show that the sensor passed directly over the object" from the question "assuming that the sensor passed directly over the object, what is the resulting geolocation accuracy?"

To measure the geolocation accuracy, the shallow water data sets were closely examined. Data sets where the link to the GPS base station was intermittent, or where the GPS fix quality was going in and out of RTK fixed-integer mode, were excluded, resulting in eight data sets. The calculated line paths of the sensors over the ground truth objects were visually examined.

In the images below, the black circles represent the ground truth locations, and the blue lines represent the calculated sensor paths.

7.3.1.1 Geolocation Accuracy of EM61 Data

Because no data set contained one line that went directly over every object, a method was devised for finding the closest approach. The geolocated EM61 data from each data set were read into Oasis, and the "pick peaks along line" tool was used. A 10mV detection threshold on gate 3 was selected, as this threshold was above the noise floor and reliably picked targets whose line paths appeared to cross over or near the ground truth locations. The autopicked targets were written out to file and then read into a piece of software that, for each ground truth location, found the closest autopicked target location. If the closest target location to a ground truth location was greater than one meter away, we examined the data to find the cause, and saw that the closest sensor path was sufficiently far from the target that there was no signal that stood out above the noise. We regarded these as a misses and did not include them in the statistics. The distance from ground truth, the down-track offset, and cross-track offset were recorded in a table. This was done, in each of the eight shallow water data sets, for each target. Average distances and offsets were then calculated for each data set. These are shown in the table below.

Table 7: Summary of truth statistics for EM data on shallow water test site (meters)

	average	stdev
shallow1a	0.40	0.22
shallow2	0.33	0.16
shallow5	0.33	0.17
shallow7	0.26	0.11
shallow8	0.53	0.24
shallow9	0.33	0.21
shallow10	0.42	0.21
shallow11	0.34	0.17

averages	0.37	0.19

In the demonstration test plan, we said that the objective would be met if the average error is less than 1 meter and the standard deviation is less than 50 cm. From the table, we see that the test criteria were met.

Even though the test criteria were met, it is instructive to examine several of the original individual data sets. The set “shallow9” was the only set that we acquired in ten unidirectional passes, all from Southwest to Northeast. This data set is shown below. Object #9 is missing from this data set, as its rope was inadvertently snagged on the towfish earlier in the day. There is no visible anomaly from object #15 (a 1.5” pipe right of center), as the sensor ran slightly wide of it.

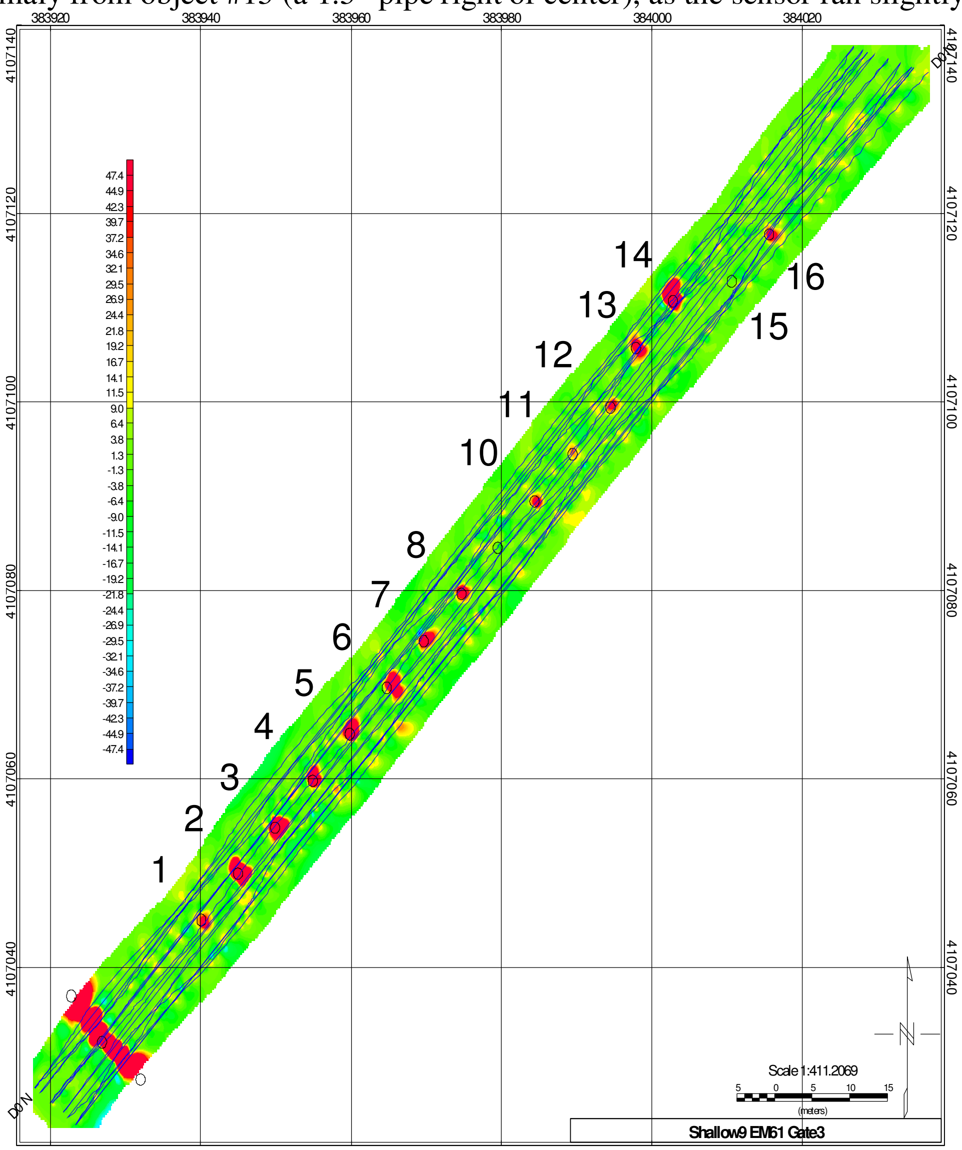

Figure 18: EM61 gate3 data from unidirectional data set "shallow9"

Because these data were acquired unidirectionally, if there was a systematic down-track offset, we would expect to see it in the results. The off-track and down-track results for this data set are shown in the table below.

Table 8: Ground truth statistics for EM data on unidirectional run shallow9 (meters)

object	distance	offtrack	downtrack
1	0.5	0.54	0.03
2	0.29	0.24	-0.11
3	0.25	-0.1	-0.21
4	0.12	0.13	-0.11
5	0.34	0.3	-0.21
6	0.86	0.11	-0.86
7	0.44	-0.4	-0.1
8	0.4	-0.34	-0.18
10	0.27	0.22	-0.15
11	0.07	0.03	-0.07
12	0.51	-0.22	-0.42
13	0.31	0.26	-0.17
14	0.15	-0.1	-0.11
16	0.1	-0.07	-0.08
average	0.33	0.04	-0.20
stdev	0.21	0.26	0.22

The down-track values for this unidirectional data set do indeed show an average systematic offset of 20cm. Object #6 (a 3” pipe horizontal down-track) appears to be particularly off. Although the orientation of this object could produce a double-humped peak that could throw the location off, we do not see a double-humped peak in the data, so that is not the source of its down-track offset. The geometric constants (GPS-to-pivot distance, sensor-to-pivot distances, boom length,) have been rechecked in the geodetic calculation, and all appear to be valid. Adjusting the EM61 latency value could bring these down-track locations into line. We used the nominal value of 0.36 seconds for all EM61 processing. Because this latency value had been used with this particular EM61 electronics console as part of MSEMS, we elected to use the latency value as-is and not adjust it as a general “fudge factor.”

In contrast with the unidirectional data set “shallow9,” the set “shallow10” shown below was acquired in racetrack or “zamboni” fashion, where the traverses on the northern side of the shallow water test plot were acquired driving the boat Southwest to Northeast, and those on the southern side were acquired Northeast to Southwest. In terms of the ability to stay on pre-determined traverses, shallow10 appears to be the best set of data we acquired. As with “shallow9,” object #9 is missing from this data set, as its rope was inadvertently snagged on the towfish earlier in the day. There is no visible anomaly from object #10 (a vertical 1.5” pipe), as the sensor ran slightly wide of it. The line directly over most of the objects in the center of the test plot was acquired Southwest to Northeast, and the line to the right of that was acquired in the opposite direction. Although there are visible artifacts in the interpolated data due to the way that Oasis attempts to drape a fitted surface in irregularly-spaced data (for example, the bulge in the pipe anomaly at the Southern end of the test plot), the fact that there are no visually apparent chevrons in the racetrack-acquired data shows that any down-track offsets are relatively minor.

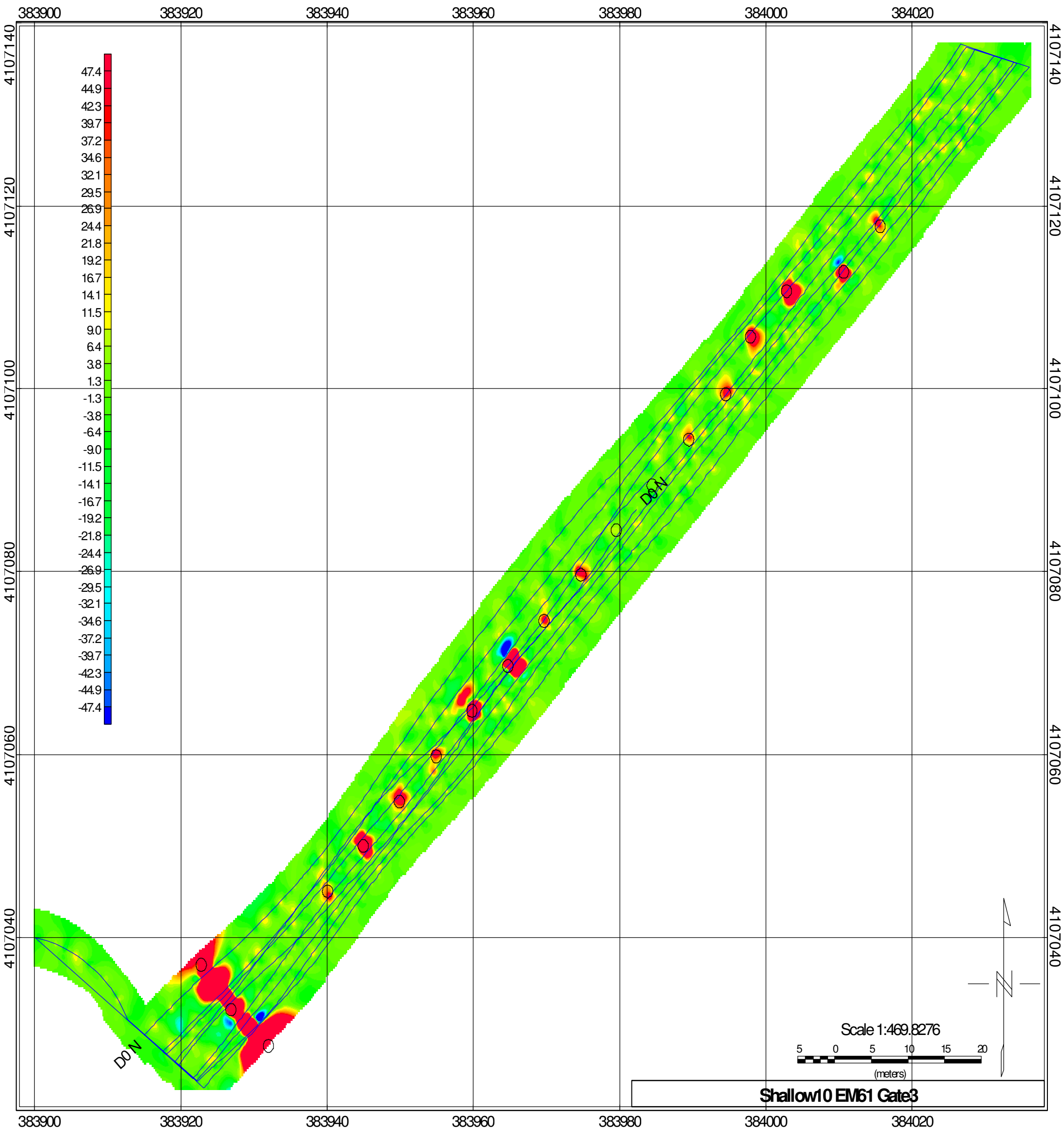

Figure 19: EM61 gate3 data from "zamboni" data set "shallow10"

The statistics for data set "shallow10" are shown below. Since the data set is not unidirectional, the absence of a systematic down-track offset is not surprising.

Table 9: Ground truth statistics for EM data on zamboni data set "shallow10" (meters)

target	distance	offtrack	downtrack
1	0.66	0.63	0.29
2	0.69	-0.71	-0.01
3	0.58	-0.47	-0.31
4	0.56	-0.49	-0.1
5	0.27	-0.22	-0.07
6	0.69	0.56	-0.46
7	0.15	-0.06	-0.12
8	0.61	-0.59	0.04
11	0.32	-0.29	-0.11
12	0.44	0.13	-0.43
13	0.27	-0.26	-0.06
14	0.15	0.02	-0.15
15	0.19	-0.15	0.12
16	0.23	-0.2	0.11
average	0.42	-0.15	-0.09
stdev	0.21	0.39	0.21

Below we show data set “shallow7.” This set was acquired before we re-configured the guidance system with a separate forward-mounted GPS antenna that helped us to stay on track. As such, in order to cover the test plot, we “painted the track” with redundant lines.

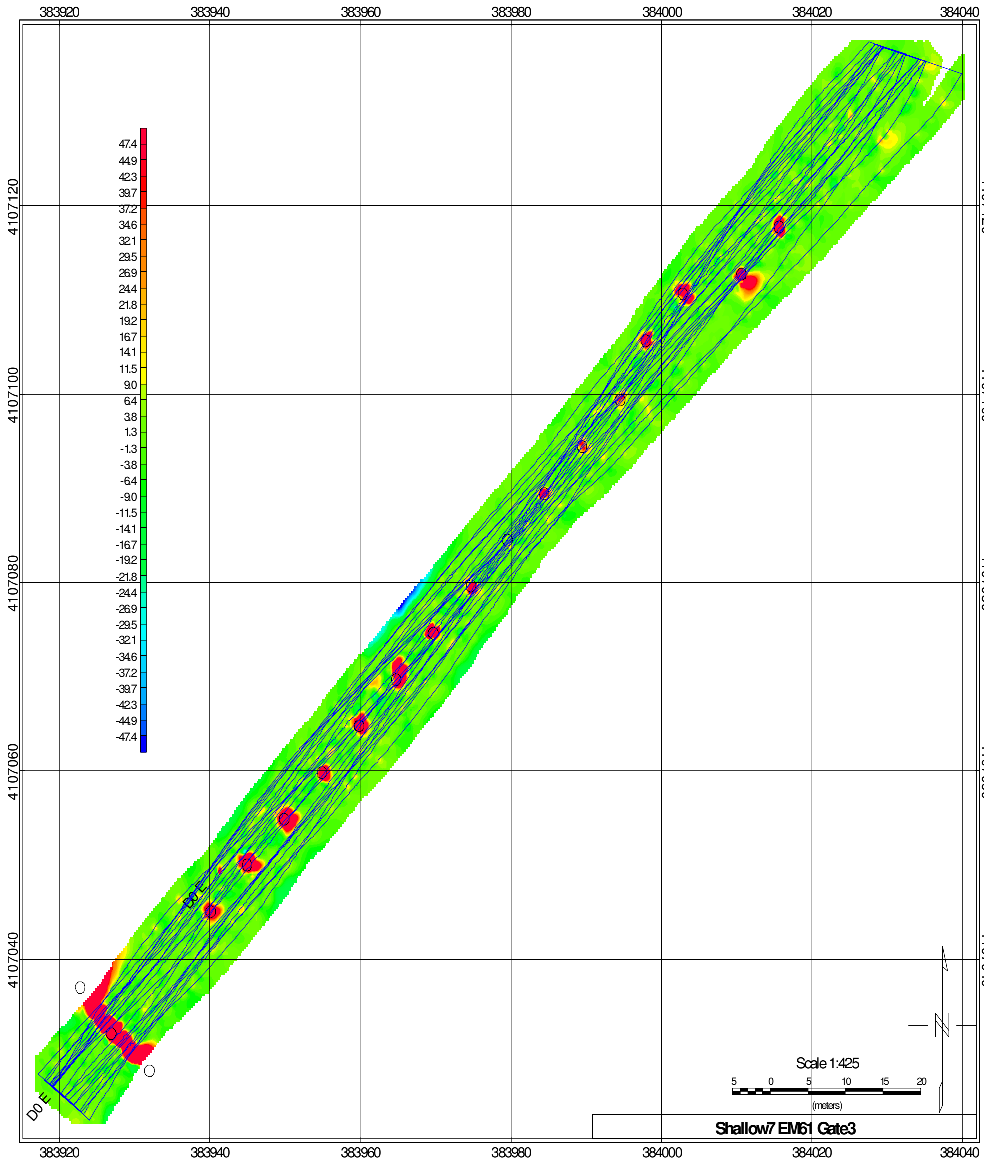

Figure 20: EM61 gate3 data from data set "shallow7"

Because these were taken in nearly random directions (that is, not unidirectional, not a Zamboni pattern, and not in an adjacent bidirectional pattern), they perhaps represent a worst case in terms of both possible chevron effects as well as geolocation inaccuracy. A visual examination of the image above, though, does not show chevron effects, either on the pipe at the Southern end of the track, nor on the objects. The ground truth analysis is below:

Table 10: Ground truth statistics for EM data on data set "shallow7" with lines in random orientations (meters)

target	distance	offtrack	downtrack
1	0.06	0.07	-0.05
2	0.25	-0.27	0.02
3	0.21	0.16	-0.17
4	0.29	0.35	-0.05
5	0.2	-0.12	-0.12
6	0.34	0.38	-0.04
7	0.28	0.07	-0.28
8	0.25	-0.19	0.14
9	0.5	0.34	0.37
10	0.12	-0.07	0.1
11	0.11	0.12	0.03
12	0.33	-0.12	-0.26
13	0.32	0.26	0.18
14	0.42	0.41	-0.08
15	0.18	-0.06	0.17
16	0.22	0.13	0.18
average	0.26	0.09	0.01
stdev	0.11	0.22	0.18

Lastly, in discussing geolocation accuracy, it is worth noting that larger systems such as the Marine Towed Array (MTA) utilize an array of sensors, creating a wide co-registered swath of data with pass. In contrast, USEMS does not have an array of sensors – it has a single EM61 and single magnetometer. The ability of USEMS to acquire non-unidirectional data that visually appears chevron-free and has the average and standard deviations listed above, is essential to its potential usefulness. That is, if USEMS or any other single-sensor system did not have sufficient geolocation accuracy to create chevron-free data from passes of alternating directions, it would not be useful.

7.3.1.2 Geolocation Accuracy of Magnetometer Data

Because the dipolar response of the magnetometer is more complex than the unipolar response of the EM61, the method of extracting the coordinates of the strongest peak that was employed to determine the geolocation accuracy of the EM61 data was not appropriate for the magnetometer data. Instead, we used Oasis' UxAnalyze tool to fit magnetic dipoles to the magnetometer data at the target locations in the test strip. UxAnalyze rejected some of the strongest dipoles, with the curious message "anomaly not strong enough to fit" (SAIC's Tom Furuya, the engineer who coded the software behind UxAnalyze, said "I am not sure why the weaker dipoles fit but not the strong ones. Sometimes if there are spikes in the data it causes problems with the inversion converging. This may happen over strong anomalies."). These rejected items were not included in the statistics. Averaging the geolocation statistics of all fit anomalies within each data set, we generated the summary table below, which shows that the average geolocation accuracy of the magnetometer data is slightly better than that of the EM data (30cm as opposed to 37cm). The data set "shallow8," with the worst average accuracy, is an incomplete data set with paths that do not completely cover the objects, and is also one where 13 of the 15 anomalies would not fit, and the two that succeeded in fitting were weak.

Table 11: Summary of truth statistics for magnetometer data on shallow water test site (meters)

	average	stdev
shallow1a	0.19	0.18
shallow2	0.17	0.19
shallow5	0.19	0.23
shallow7	0.17	0.21
shallow8	0.84	0.01
shallow9	0.36	0.29
shallow10	0.20	0.12
shallow11	0.29	0.27
Averages	0.30	0.19

The magnetometer data from the survey “shallow10” (acquired in racetrack fashion) are shown below. Object #9 is missing, as its rope caught on the towfish and was pulled out of the track earlier in the day.

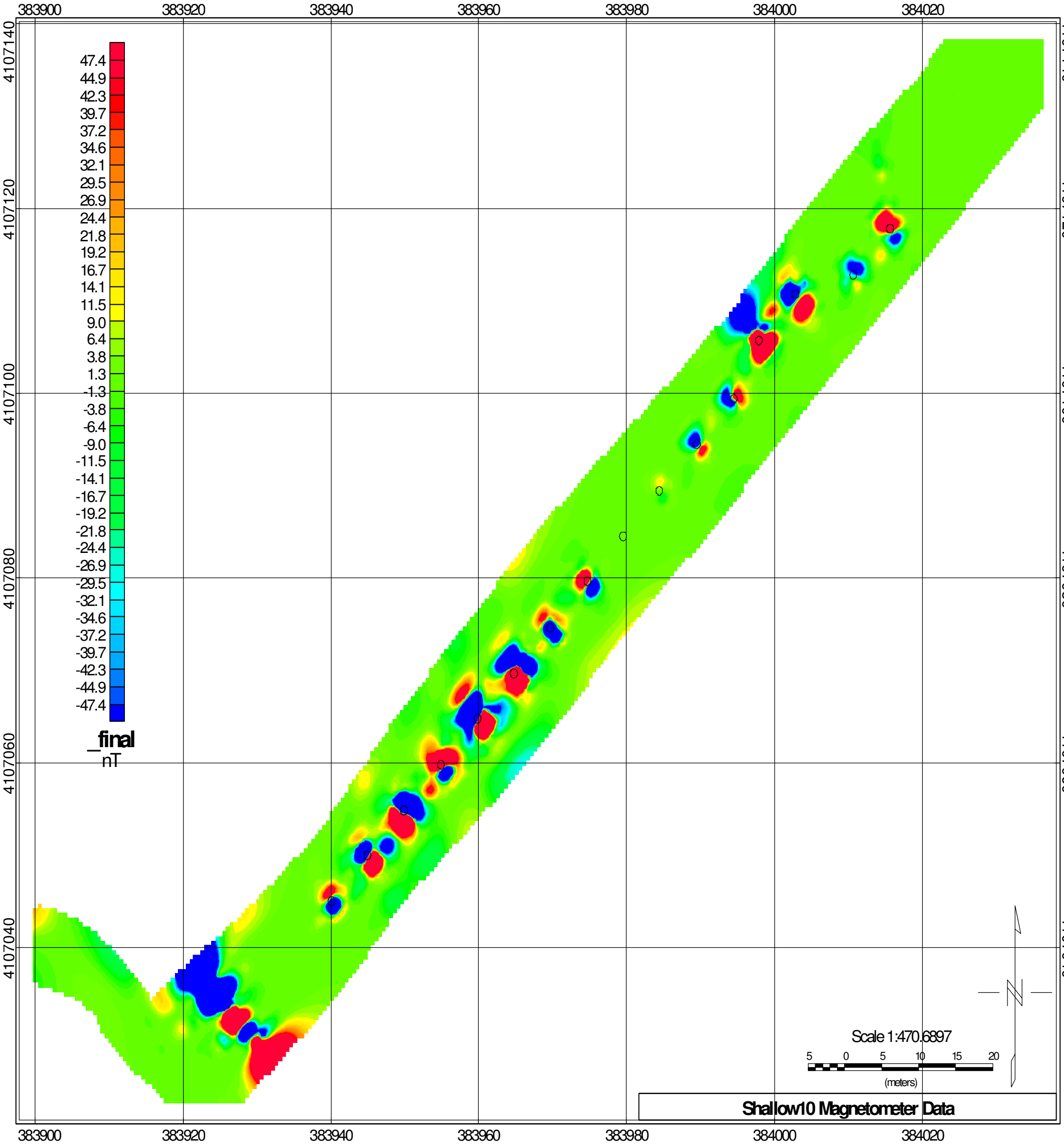

Figure 21: Magnetometer data from data set "shallow10"

7.3.2 Analysis of Deep Water Test Plot Data

Because the water depth in the deep water test plot was too deep to stand up in, objects were emplaced by dropping them over the side of the boat. The goal was to place them within approximately a meter of their planned locations. Their actual ground truths are not known (they were not shot in with an RTK GPS like objects in the shallow water test plot). Four objects were dropped, but early in the survey, despite J-shaped lines attached to buoys intended to avoid snagging, one object was snagged and dragged to the side. Thus all data in the deep test plot contain three objects.

7.3.2.1 Visual Analysis

In all of the images below, the grid squares are five meters on edge, the color scale is +- 50nT for magnetometer data and +- 50mV for EM61 gate3 data, and the white circles represent the planned object locations. Unless noted, the speed was approximately 1.5 meters per second. The anomalies from the first and third objects consistently overlay the planned locations, while the second object consistently appears to the left of the planned location, indicating that it was dropped further to the west than planned. The blue lines represent the line paths of the magnetometer and EM61 sensors, and the white circles represent the planned object locations.

Anomalies in the magnetometer data are clear and strong at 0.5m, 1.0m, and 1.5m fish heights above bottom, and visually correlate well with the planned object locations. In the EM61 data, we only see anomalies visually correlated to the ground truth locations in the data taken at fish heights of 0.5 meters; we do not see EM61 anomalies that clearly stand out from the noise in the 1.0 meter and 1.5 meter fish heights. Although the EM61 data presented below uses gate3, we have examined the gate2 data and the results are the same. The gate1 data is too noisy for examination.

The geolocation calculation was performed the same way as when processing the shallow water data – it employed the position data and heading data from the GPS, the pitch and roll data from the boat inclinometer and fish inclinometer, and the RPS data from the boom. However, all of the data on the shallow water test site was acquired during calm conditions (Sea State 0), whereas some of the data from the deep water test site was taken during moderate wind and wave conditions (Sea State 1). As the boat pitches and rolls on the water, that motion is registered in all of the above sensors, and the geolocation calculation uses all of these inputs. So long as they add constructively (ie, when the boat pitches forward, this registers as positive pitch on the inclinometer and a corresponding out-of-phase change appears on the boom pitch RPS). However, the inclinometers used on the boat and the fish are gravity-referenced and thus cannot distinguish between inclination and acceleration. Thus, as wave motion increases, the inclinometer tends to overshoot. This effects the calculation of the topside boom pivot point, and the error is then magnified when translated along the six meter lever arm of the boom. When this happens, the geolocation calculation produces data with wave artifacts in the line paths. These artifacts can be completely eliminated by taking the inclinometers out of the calculation, assuming that the boat has zero pitch and roll, and smoothing the boat's heading and RPS values to take out the approximately 1Hz wave motion. For the purpose of this analysis, we have chosen to process all of the data the same way and use the inclinometers, even if this means that the data sets collected in rough water have some positional artifacts in the line paths.

The images below show data set “deep17” acquired in calm water at an average fish height of 0.46 meters. All objects present very strongly in both the magnetometer and EM61 data sets. The dragged object appears in the magnetometer data off to the left and is highlighted in a yellow box.

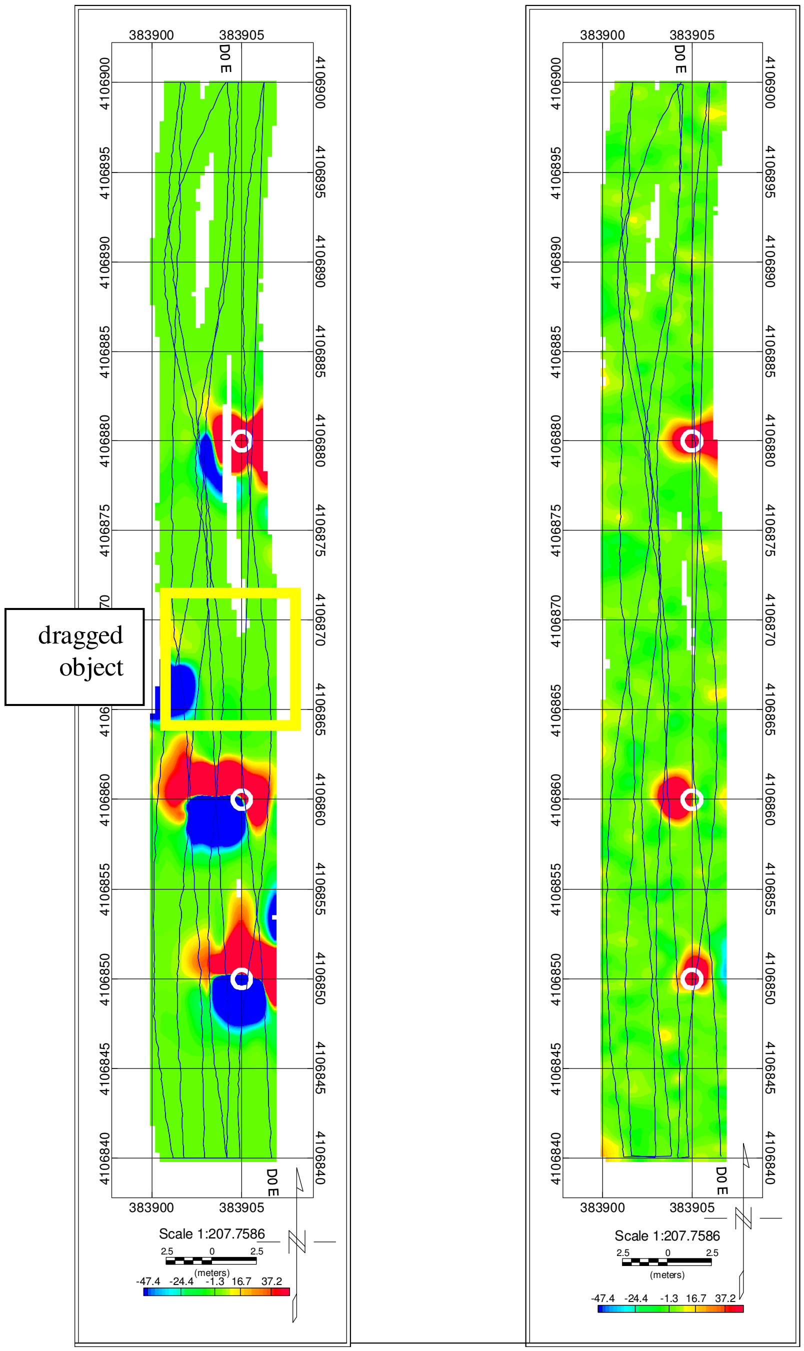

Figure 22: Concurrently collected magnetometer data (left) and EM61 gate3 data (right) from data set "deep17" at an average fish height of 0.46 meters.

The images below show data set "deep19" acquired in moderate wave and wind at an average fish height 1.02 meters. All objects are easily detected in the magnetometer data, but the increased sensor height has made the objects fall below the noise threshold in the EM61 data. Because the ground truth is unknown, we cannot tell if the fact that the line paths do not directly run over the planned locations contributes to the lack of signal.

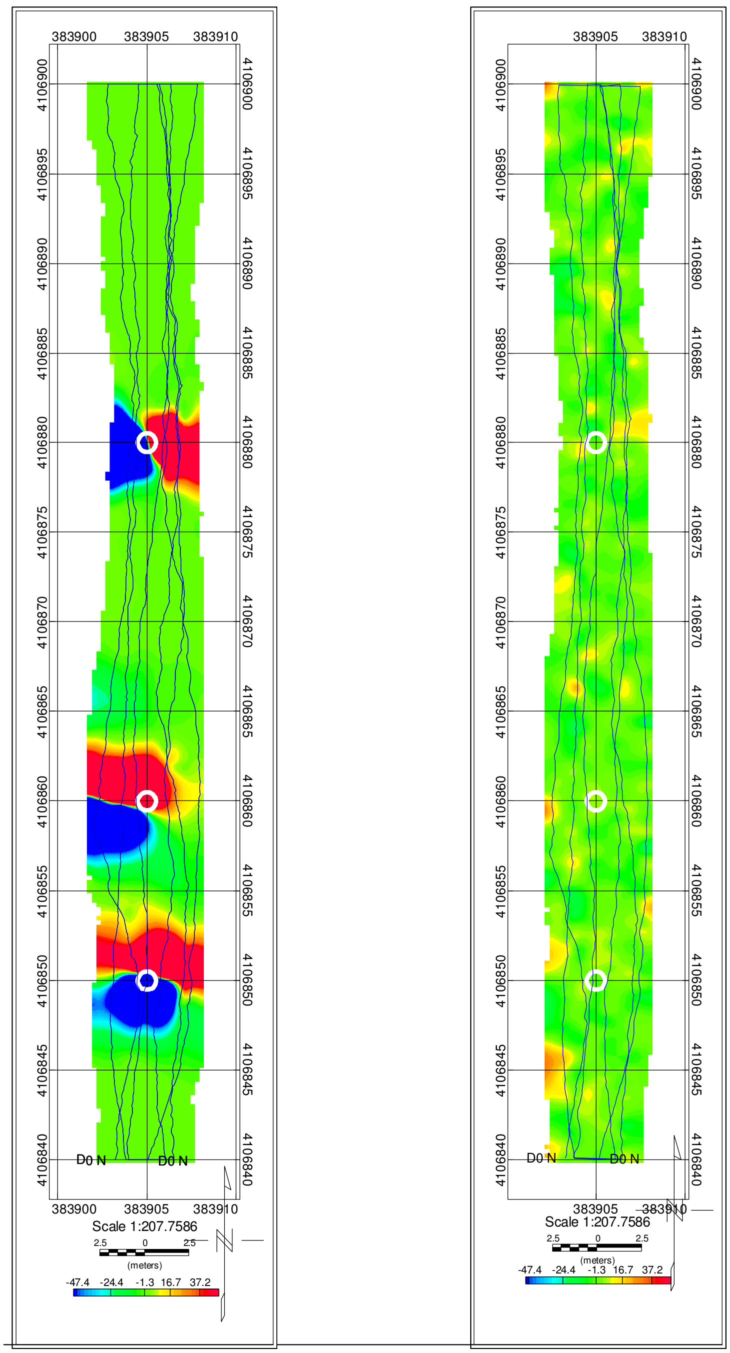

Figure 23: Concurrently collected magnetometer data (left) and EM61 gate3 data (right) from data set "deep19" at an average fish height of 1.02 meters.

The images below show data set “deep18” acquired at an average fish height 1.40 meters. All objects are easily detected with the magnetometer, but the increased sensor height has made the objects fall below the noise threshold in the EM61 data.

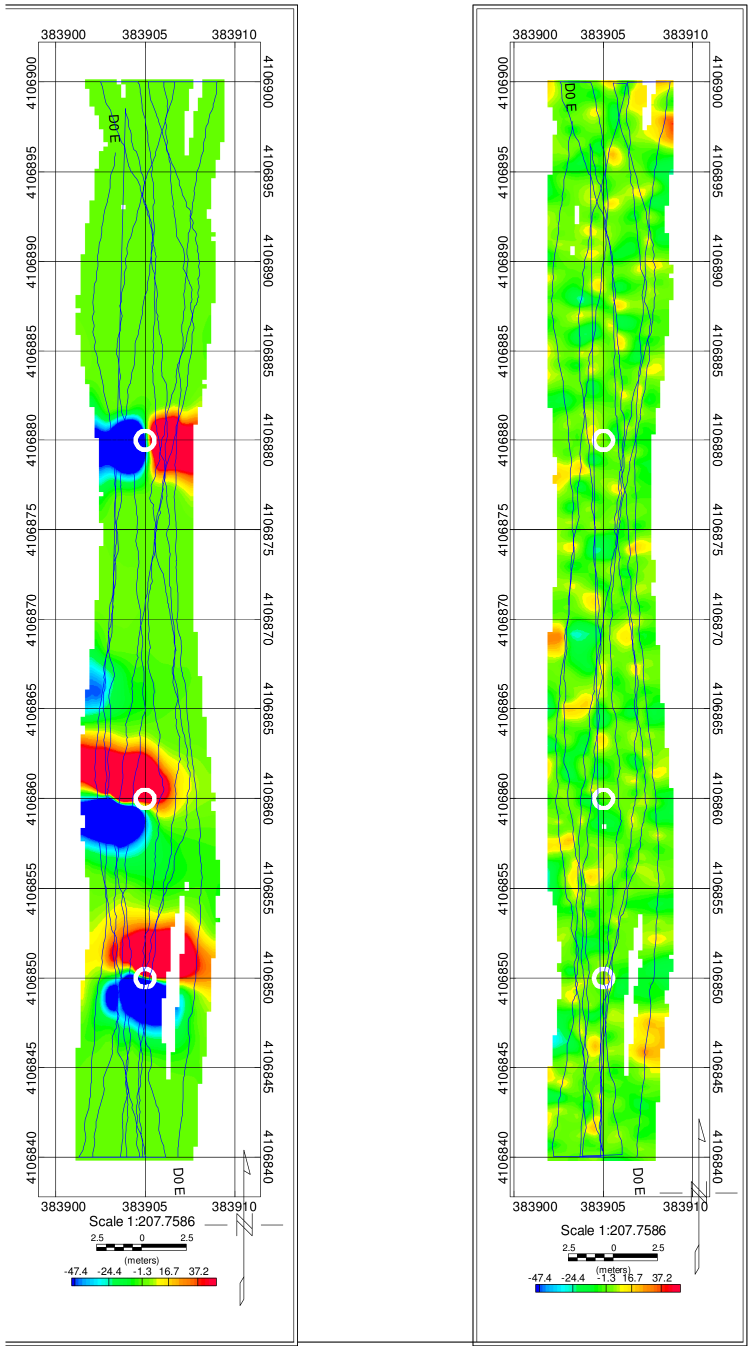

Figure 24: Concurrently collected magnetometer data (left) and EM61 gate3 data (right) from data set "deep18" at an average fish height of 1.40 meters.

The images below show data set “deep22” acquired at an average fish height 0.99 meters and at an average speed of 2.7 meters per second – nearly twice the speed of the other data sets. The magnetometer’s 75Hz data acquisition rate makes the higher speed possible; all anomalies are easily detected in the magnetometer data. There may be a weak EM61 signal at the white circle denoting the location of the Northernmost object, but an anomaly does not stand out from the noise.

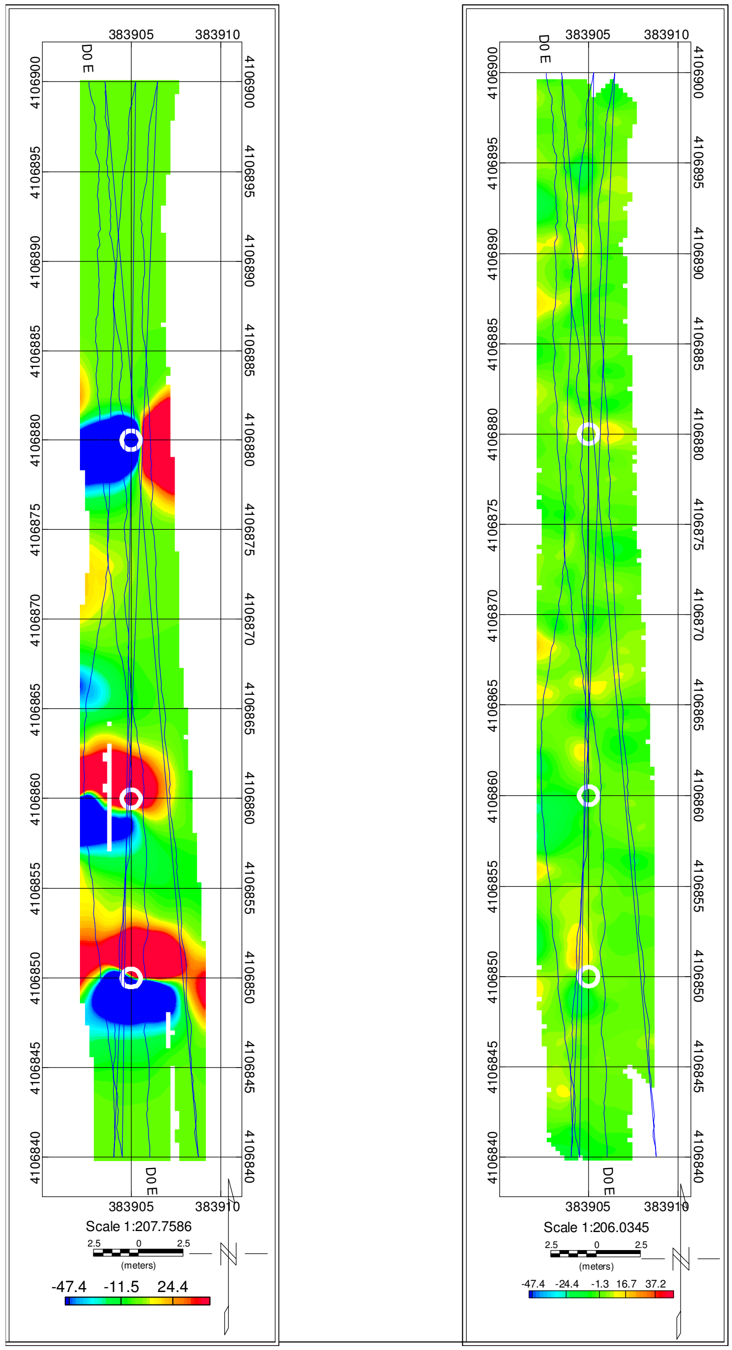

Figure 25: Concurrently collected magnetometer data (left) and EM61 gate3 data (right) from data set "deep22" at an average fish height of 0.99 meters and an average speed of 2.7 meters per second.

7.3.2.2 Geolocation Accuracy of EM61 Data

Although the deep test plot was surveyed at 0.5m, 1.0m and 1.5m standoffs, the runs that had substantial signal above noise in the EM61 gate3 data were those acquired at a fish height of

0.5m. For these data sets, we calculated the target locations the same way we did for the shallow test plot – by using Oasis to automatically pick the peaks along the profiles and by selecting the strongest peaks. These coordinates are listed in the table below. The delta_x and delta_y are also listed. These show that object #2 was substantially off in easting from where we had tried to drop it. We also list the water depth, as the different tests were conducted at a range of tidal water depths. Note that, for increased water depth, the boom pitch angle required to maintain a given height above bottom is steeper. If the boom angle was not correct, or if the geolocation calculation was not correcting using the boom angle, the target positions at different water depths would be off from each other.

Table 12: EM-derived target locations in deep test plot (meters)

	x	y	delta_x	delta_y
deep8 -- water depth 2.25				
pipe1	383905.49	4106850.22	0.49	0.22
pipe2	383903.75	4106860.36	-1.25	0.36
pipe3	383904.53	4106879.88	-0.47	-0.12
deep14 -- water depth 2.16				
pipe1	383904.49	4106849.77	-0.51	-0.23
pipe2	383903.01	4106860.46	-1.99	0.46
pipe3	383904.73	4106880.21	-0.27	0.21
deep16 -- water depth 1.85				
pipe1	383904.83	4106849.77	-0.17	-0.23
pipe2	383903.31	4106859.67	-1.69	-0.33
pipe3	383905.20	4106880.49	0.20	0.49
deep17 -- water depth 1.82				
pipe1	383905.22	4106850.37	0.22	0.37
pipe2	383903.63	4106860.19	-1.38	0.19
pipe3	383905.12	4106880.18	0.12	0.18
deep20 -- water depth 2.57				
pipe1	383905.41	4106850.27	0.41	0.27
pipe2	383903.00	4106859.87	-2.00	-0.13
pipe3	383904.86	4106879.87	-0.14	-0.13
deep21 -- water depth 2.57				
pipe1	383905.49	4106850.76	0.49	0.76
pipe2	383903.06	4106860.29	-1.94	0.29
pipe3	383904.61	4106879.62	-0.39	-0.38

Although in the table above we list the offsets in Easting and Northing from the planned object positions, because the objects in the deep test plot were dropped over the side, rigorous ground truth does not exist, and thus an accurate calculated distance from true ground truth can't be calculated. We can, however, calculate the scatter. The table below lists the average and standard deviation in northing and easting. As with the data from the shallow water test plot, these are within our success criteria.

Table 13: Statistics on EM-derived pipe locations in deep test plot (meters)

	average	stdev
pipe1 x	383905.16	0.41
pipe1 y	4106850.19	0.38
pipe2 x	383903.29	0.33
pipe2 y	4106860.14	0.30
pipe3 x	383904.84	0.27
pipe3 y	4106880.04	0.31

7.3.2.3 Geolocation Accuracy of Magnetometer Data

In the magnetometer data the signal over the targets is strong not only in the 0.5m height data but also the 1.0m and 1.5m height data. This is not the case in the EM61 data, where only the data acquired at 0.5m standoff produced viable signal to noise. Thus, the deep magnetometer data present a richer data set than the deep EM61 data. We performed the same analysis on the deep water magnetometer data that we did on the shallow water magnetometer data – we fit the anomalies with UxAnalyze to extract their locations. We had similar challenges with UxAnalyze. On data sets where only a single line path fell within the analysis window, we received the "anomaly not strong enough to fit" message. While we could've used threshold detection on these objects, the dipolar nature of magnetometer data makes the location of threshold-detected peaks geodetically inaccurate (that is, the object is not directly beneath the maximum; it is on a line connecting the max and min, offset from the max in the direction of the min). Because we did not wish to confuse these two techniques, objects where UxAnalyze failed are denoted with asterisks in the coordinate field.

Table 14: Magnetometer-derived target locations in deep test plot (meters)

	fishheight	waterdepth	x	y
deep8	0.49	2.25		
target1			383905.00	4106850.31
target2			***	***
target3			383905.22	4106880.13
deep14	0.5	2.16		
target1			***	***
target2			***	***
target3			383906.07	4106879.64
deep16	0.54	1.85		
target1			383905.28	4106850.26
target2			***	***
target3			383904.76	4106880.03
deep17	0.46	1.82		
target1			383905.03	4106850.36
target2			383903.31	4106860.22
target3			383904.27	4106879.94
deep3	1.02	2.26		
target1			383905.02	4106850.33
target2			383903.52	4106860.19
target3			383904.95	4106879.99
deep7	1.03	2.31		
target1			383905.39	4106850.35
target2			383904.47	4106860.23
target3			383905.21	4106879.87
deep13	0.98	2.2		
target1			383905.46	4106850.33
target2			***	***
target3			383904.89	4106880.14
deep10	1.51	2.35		
target1			***	***
target2			383903.41	4106860.40
target3			***	***
deep12	1.54	2.31		
target1			383905.06	4106850.42
target2			***	***
target3			***	***

As with the EM61 deep test plot data, we calculate the spread. The table below lists the average and standard deviation in northing and easting. As with the data from the shallow water test plot, these are within our success criteria.

Table 15: Statistics on magnetometer-derived pipe locations in deep test plot (meters)

	average	stdev
pipe1 x	383905.21	0.17
pipe1 y	4106850.36	0.10
pipe2 x	383903.54	0.39
pipe2 y	4106860.28	0.08
pipe3 x	383905.07	0.43
pipe3 y	4106880.02	0.16

7.4 Noise

In the demonstration test plan, we said that the objective would be met if the average noise for the USEMS EM61 and magnetometer data acquired at Plum Tree Island (PTI) is no greater than 1.2 times the noise recorded at MSEMS' demonstration at Yuma Proving Grounds.

Below we compare noise in the magnetometer data acquired at Yuma with MSEMS and at Plum Tree Island with USEMS. In both data sets we selected a portion of a survey line acquired over a section of the test plot where there were neither emplaced targets nor obvious clutter, and extracted the statistics from the background-leveled magnetometer data. The MSEMS YPG magnetometer data are noisier than the USEMS PTI data due to a) the presence of magnetically-active geology at YPG, and b) the use of older firmware in the original MSEMS interleaving hardware that stored the magnetometer data as integers instead of floating point numbers (this has since been changed). Nonetheless, the fact that the standard deviation of the USEMS magnetometer data is more than an order of magnitude less than that of the MSEMS data is clear indication that the interleaving is functioning as designed and that USEMS is collecting high-quality magnetometer data between EM61 pulses.

Table 16: Comparison of Magnetometer Noise, MSEMS at YPG and USEMS at Plum Tree Island

	mag min	mag max	mag av	mag stdev
MSEMS	-7.00	6.00	-0.15	2.50
USEMS	-0.43	0.50	0.01	0.14

Below we compare noise in the EM61 data acquired at Yuma with MSEMS and at Plum Tree Island with USEMS. In both data sets we selected a portion of a survey line acquired over a section of the test plot where there were neither emplaced targets nor obvious clutter, and extracted the statistics from the background-leveled EM61 data. The EM61 data from USEMS is substantially noisier than the MSEMS data, particularly in the earlier time gates. USEMS EM61 noise levels varied somewhat from data set to data set, but none remotely approached the lower noise levels of MSEMS. The statistics in the table below are extracted from a representative data set, "shallow9."

Table 17: Comparison of EM61 Noise, MSEMS at YPG and USEMS at Plum Tree Island

	min	max	average	stdev
MSEMS gate1	-1.08	1.72	0.22	0.67
MSEMS gate2	-2.47	0.53	-1.24	0.69
MSEMS gate3	-1.76	1.24	-0.51	0.7
MSEMS gate4	-1.6	1.69	-0.15	0.74
USEMS gate1	-70.76	69.7	0.92	21.47
USEMS gate2	-30.84	20.78	-0.19	7.59
USEMS gate3	-16.34	24.65	0.27	5.27
USEMS gate4	-5.7	5.7	-0.01	1.75

All the EM61 data sets on the shallow water test plot were noisy in comparison with terrestrial data, particularly in the earliest time gate. The table below summarizes the standard deviations of the noise in the eight data sets collected on the shallow water test plot.

Table 18: Standard deviation of EM61 noise on shallow water test plot (mV)

	gate1	gate2	gate3	gate4
Shallow1a	19.5	6.61	3.59	1.9
Shallow2	55.75	11.5	6.88	5.9
Shallow5	19.85	6.93	3.9	1.76
Shallow7	22.12	5.8	3.82	2.2
Shallow8	19.79	7.18	5.17	2.2
Shallow9	21.47	7.59	5.27	1.75
Shallow10	55.48	6.72	5.52	4.71
Shallow11	69.38	5.17	4.53	3.13
Average	35.42	7.19	4.84	2.94

If we calculate the average standard deviation of all gates from all shallow water tests, and take the ratio of that to the average MSEMS standard deviation from YPG, the result is 18.5.

On most data sets, the EM61 noise was relatively constant across a survey, but on several of the data sets the noise could be observed surging. Below we show the data set “shallow5.” The strong peaks in the plot represent real signal over test plot objects, but strong spectral noise is clearly visible, particularly in gate1 (red). The peak-to-peak of the noise in gate1 at the start of the run is approximately 50mV, but in the later part of the run it can be seen to surge well over 100mV. Even the spectral noise on gate4 (pink) can be seen to be surging.

EM61 Signal and Noise, Shallow5

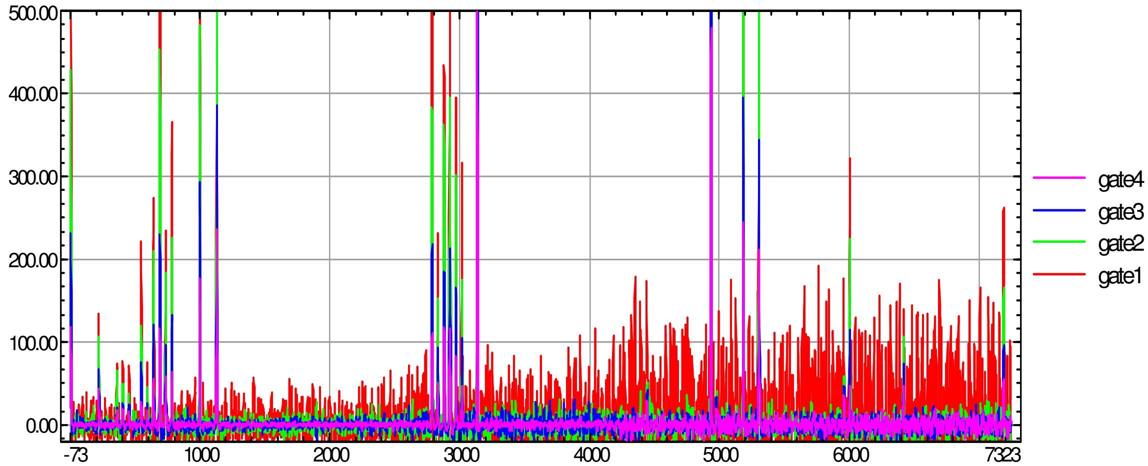

Figure 26: Surging noise in EM61 data set "shallow5" in mV

We also observe the surging and retreating EM noise, particularly on gate1, in all of the traverse data sets acquired off Plum Tree Island. In the figure below, we plot “area5,” representing approximately three hours of data acquisition including data acquired in calm water in the Back River, data acquired in Sea State 2 (high wind and wave) off Plum Tree Island, and data acquired across the deep channel into the Back River where we angled the dive planes down to drive the fish to its maximum depth. Neither the speed of the boat, the depth of the water, the depth of the fish, the roll and pitch of the boat and the fish, nor the angles of the boom have any correlation with the surge and retreat of the noise on gate1.

EM61 Signal and Noise, Area5

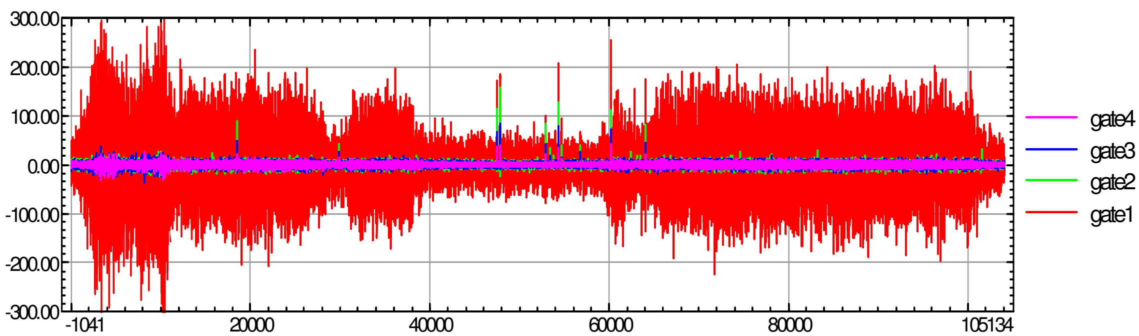

Figure 27: Surging noise in EM61 data set "area5" in mV

Although the EM61 noise at Plum Tree Island was much less on the later time gates than on gate1, it was still far larger than what is commonly experienced on EM61 terrestrial survey. This did not render USEMS’ EM61 useless, but it did require targets to have higher signal than on terrestrial surveys to stand out from the noise.

We do not know what the source of the EM61 noise at Plum Tree Island was. It is possible that it was related to the conductive properties of the salt water. However, we do not know why noise from this source would not remain constant throughout the demonstration. We have broached the noise issue with Geonics; they mention intrusion of water into the EM61-S coil as a possibility. Andy Schwartz of USACE observed similar noise levels in EM61-S data acquired in 2005 and suspected a poor wet-mateable connection between the coil and cable (water poured from the connector upon system disassembly of USACE's system during demobilization). Similar noise problems were observed in data from a USACE EM61-S survey of Plum Tree Island in 2009. In a personal communication with Ken Hayes of Aqua Survey, Mr. Schwartz was told similar issues were observed in Aqua Survey's prototype marine EM61 array, but that their electrical engineer resolved the problem. No further details were offered by Mr. Hayes. Note that USEMS uses the identical interleaving hardware and the identical EM61 electronics console (that is, the same physical pieces of hardware) as the man-portable MSEMS, which does not exhibit this noise. Note also that the technical approach of interleaving does not alter the EM61 electronics at all; a cable is merely connected to the sync connector on the EM61 electronics console and used to control the magnetometer sampling. Because of problems during USEMS' testing with ground loop issues, optical isolators were put on the EM61 and magnetometer serial outputs, as well as on the EM61 sync pulse. Further, the EM61 is operated on a completely separate battery circuit than either the magnetometer or the data acquisition computer and GPS. Thus the EM61 electronics in USEMS should be better electrically isolated than those in MSEMS. This configuration of isolated power and optical isolators on the serial and sync ports were shown, in the lab, to produce lower-noise data than non-isolated configurations.

After the Plum Tree Island survey, SAIC conducted extensive tests to isolate the noise source. USEMS' EM61 coil was taken out of the towfish, configured as a COTS EM61-S, suspended in air, then submerged in a salt water-filled fiberglass tank at the University of Rhode Island's Marine Ecological Research Lab (MERL) facility. Noise levels were nominal and did not increase when submerged. This indicated that there was not any apparent problem with the coil or connector, and thus implied that the noise was systemic in USEMS. The assembled towfish was then used for noise testing inside SAIC's building in Waltham MA. Although this is a high-noise environment, comparative tests of different configurations were performed by collecting 20 minutes of data, performing background leveling, and examining the standard deviation. The following corrections and modifications were made to USEMS. Each of these was found to significantly reduce EM61 noise in the building.

- An intermittent connection in the EM61 power cable was discovered and replaced.
- Serial optical isolators had already been employed on the computer's EM61 and magnetometer ports to break subtle ground loops that were formed through the serial ground to the computer, but these isolators were moved from computer's DB9 connectors and instead placed as close as possible to the serial devices generating the data.
- In addition, other serial optical isolators were placed on every serial device, even those devices not suspected of generating ground loops that could affect the EM61.
- It was found that the system power connections, which relied on using a shared ground buss that had originally connected the grounds on the EM61, magnetometer, and system battery stacks, was contributing noise to the EM61 because the shared ground buss meant that power

cables were run individually rather than benefiting from the noise cancellation of having the power and ground be part of a twisted pair. All system power connections (MagLog computer, GPS, encoders, PLC, etc) were re-wired with twisted pair wiring.

- It was found that the EM61 battery wiring, which had a two-pin quick-disconnect SAE connector, was a source of noise whenever this cable was jostled. It was replaced with a twisted pair of wires running directly from the battery to the EM61 electronics console, with no intermediate splices or connectors.
- Certain power cables were running from stern to bow and again from bow to stern simply so power could be switched on at a single bow-mounted power panel. These switches were relocated to from the bow to the stern of the boat to minimize long runs of cable.

Collectively, these modifications reduced the USEMS EM61 noise (as measured inside the SAIC building) by a factor of 5.5, making us hopeful that EM61 noise levels will be nominal the next time USEMS has the opportunity to be in the water.

7.5 Track Guidance

During the demonstration, three people operated the boat, and each used a different primary method of track guidance. Dr. Roy Richard relied completely on the Trimble EZ Guide. Davis Sanford relied on landmarks on the shoreline, glanced at the traverses shown on the fish operator's station in MagLog, and used the EZ Guide as a secondary reference. John Morris, who operates a variety of marine vessels for hydrographic applications, suggested that we set up his notebook computer running the commercial hydrographic package HyPack and feed it the same GPS strings being fed to the EZ Guide. Although any 17' boat is affected substantially by wind, wave, and wake, and although Mr. Morris, using HyPack, did the best job at line following, all three operators complained that, when correcting the boat's path and trying to bring it on track, there seemed to be a surprisingly long lag between steering correction and visible effect on the boat's course. This lag sometimes produced overcorrection. Near the end of the demonstration we realized what was causing the lag. The Trimble MS860II heading receiver – the primary geolocation instrument on the boat – has two antennas, but the position of only one of the antennas is available as a NMEA output. The other antenna's position is used internally by the receiver to calculate the heading, but it is not available as a NMEA output. When we realized this, we mounted a Trimble R8 GPS receiver and antenna in the bow of the boat and fed its NMEA output to the lightbar and the notebook computer running HyPack. The last four data sets (shallow8 through shallow11) were acquired in this way, and show much better line following than the earlier data sets. For comparison, below we show the first set (shallow1a) and one of the last sets (shallow10)

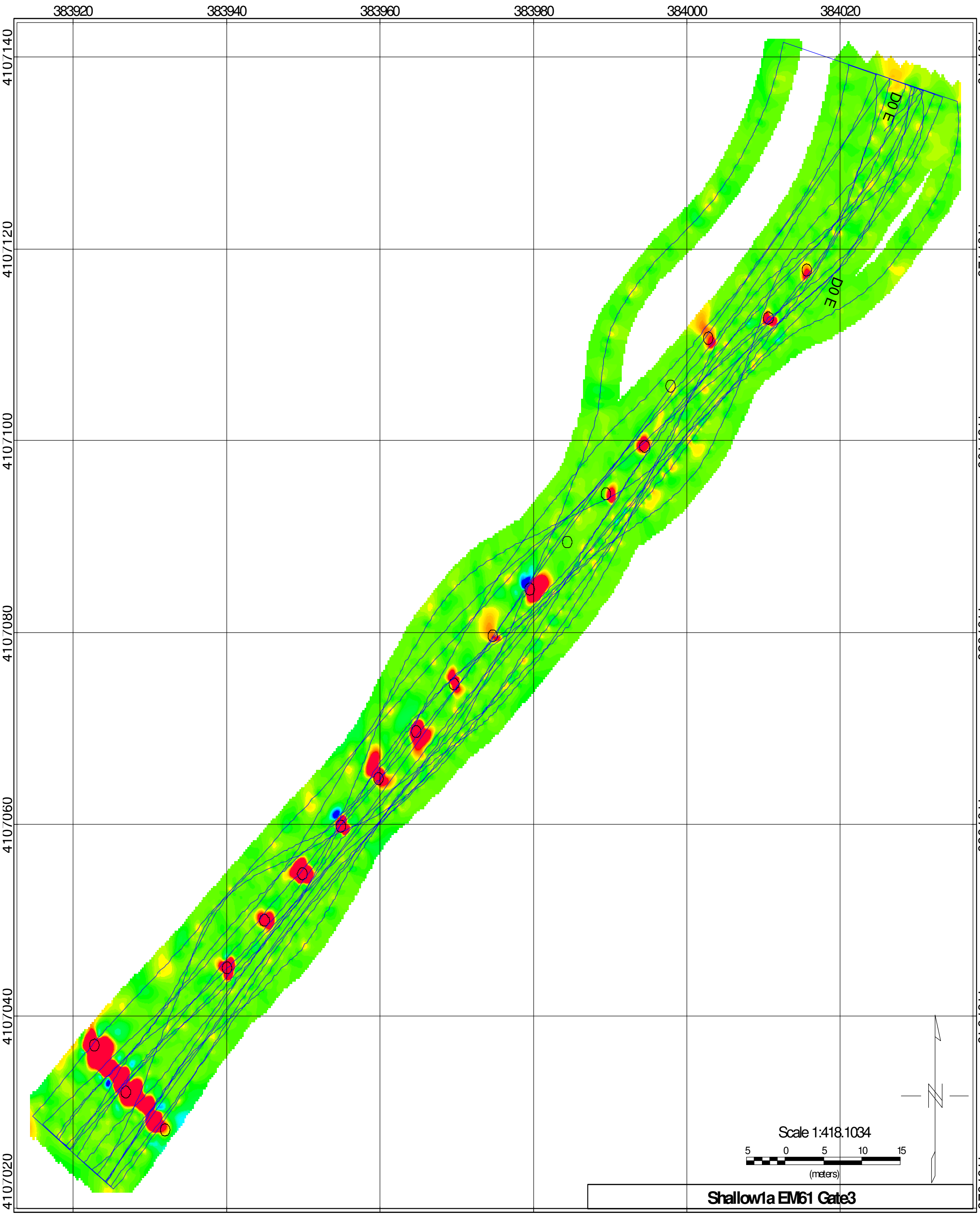

Figure 28: Data set taken early in the survey showing poor line following

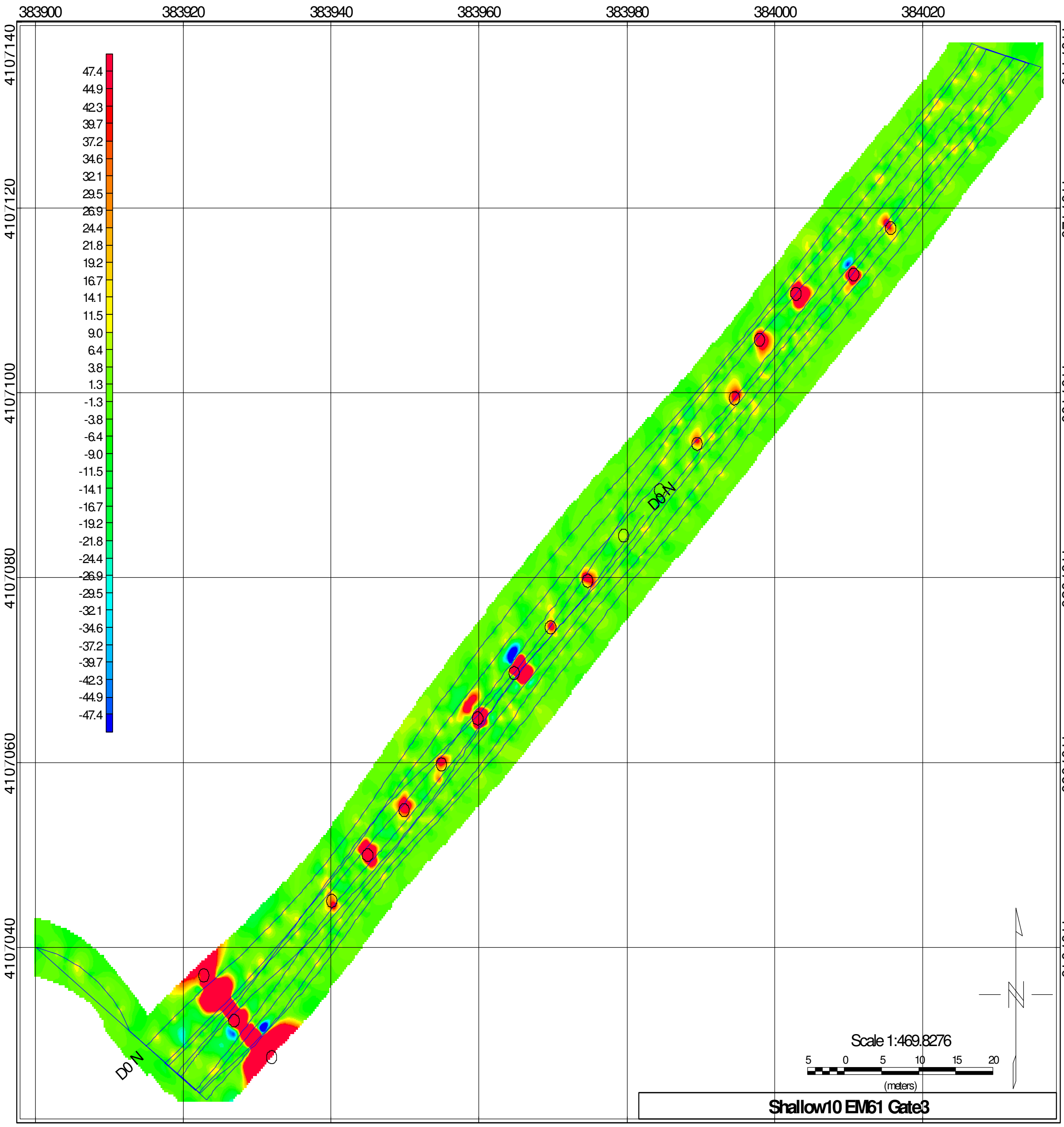

Figure 29: Data set taken near the end of the survey showing dramatically improved line following

In the table below, we report the results of Oasis' "footprint coverage" tool. A boundary file was made using the endpoints of the left and rightmost survey lines. A one meter footprint was employed. Note that the footprint coverage tool does not attempt to calculate how well any particular planned line was followed; it merely calculates the percentage of area covered. For example, "shallow7," the run with the highest coverage, occurred before we mounted a GPS in the bow of the boat, and was an attempt to "paint the track" by running lines back and forth, over and over, multiple times. Conversely, "shallow8," the first file acquired with the relocated guidance GPS, was an attempt to see if the change helped the operator to follow lines; we did not attempt to collect a full set of lines. For this reason, although the table below uses the metric that we said we would use in the demonstration test plan (Oasis' footprint coverage), it creates the mistaken impression that there was no progression in the ability to follow pre-planned tracks. This is definitely not the case, as we showed by presenting the plots of the line paths themselves.

Table 19: Percent coverage for shallow test site surveys

	percent
shallow1a	81.0
shallow2	72.2
shallow5	65.6
shallow7	89.7
shallow8	41.8
shallow9	84.3
shallow10	79.3
shallow11	80.0

Removing the outlier "shallow8" (as we did not attempt complete area coverage in that survey), the average foot print coverage is 78.9%, or 21.1% missed area. In the demonstration test plan, we said that the objective will be met if the missed area is less than 5%. By this metric, the success criteria were not met. However, we have the following observations:

- While wind, wave, currents, and wake place limits on the ability to follow pre-planned lines and generate survey data with high footprint coverage, an experienced operator using tools that he or she is familiar with can do much better than an inexperienced operator trying to drive while gain familiarity with the tools.
- While MagLog's display of real-time traverses on top of the planned tracks is useful, and while the lightbar's display of an off-track indicator is useful, these should be supplemented with a small computer running HyPack or the equivalent that puts the display of both of these at the operator's fingertips.
- A GPS located in the forward section of the boat (or a simulated GPS string whose location has been translated to the bow of the boat) should supply the required NMEA strings to the guidance tools.

7.6 Operability By A Two Man Crew

In the demonstration test plan, we said that this objective was met if the essential survey functions (getting the towfish into and out of the water, attaching the boom and towfish, and conducting survey operations) were conducted by the designated boat operator and fish operator.

The system was secured nightly at a slip at the marina. Although it would have been possible to leave the fish and boom in the water for the entire operation, concern over the possibility of damage by small waves beating the equipment into the pier caused us to decide to put the fish and boom in the water every morning and pull it out every evening. This was sometimes accomplished using the jib crane on the bow of the boat, but sometimes the fish was simply pulled out of the water and pulled up onto the dock by two people. Although the two people were not always the boat and fish operator, we consider this success criteria to have been met; there was no deployment or retrieval function that required a third person.

Survey operations were always conducted by the fish operator (Robert Siegel) and whichever of the three boat operators were driving. Thus we consider the success criteria to have been met.

7.7 Operators Presented With Sufficient Information

In the demonstration test plan, we said that this objective was met if the boat operator and fish operator were able to, respectively, pilot the boat and follow survey lines, and keep the fish the planned standoff above bottom.

The fish operator concentrated primarily on the window in the MagLog display showing the digital numeric reading from the altimeter in the fish (e.g., 1.0 meters), and nudged the joystick to keep the fish at the desired altitude. Although the real-time altimeter reading was noisy, the operator was able to "eyeball average" the data with little difficulty. It is possible to have MagLog display the difference between the boat altimeter and the fish pressure transducer to generate a stable fish height reading, but this was not necessary. Thus, for the fish operator, the success criteria were met.

The boat operator concentrated primarily on trying to keep the boat on pre-planned lines. As described above, line following was difficult due to wind, wave, currents, and wake, and the absence of a dedicated boat guidance computer, but the single largest factor affecting line following was the location of the GPS antenna feeding the guidance system. Once this was corrected, line following improved dramatically. Thus, for the boat operator, the success criteria were met.

Nonetheless, we plan on integrating a dedicated traverse display computer running software such as HyPack into the boat operator's station.

7.8 Additional Traverses Off Plum Tree Island

Although it was not required in the demonstration test plan submitted to ESTCP, in addition to the shallow and deep water test plots, we ran additional traverses off Plum Tree Island that were of interest to USACE. These traverses and the areas they represent are shown in the figure below. Area1 is known from a prior USACE survey to contain a high concentration of anomalies. Area3, area4, and area5 had no prior data. The individual magnetometer and EM61 images over each area follow below. All data were acquired with a towfish height off bottom of approximately 0.5 meters.

Figure 30: Additional traverses off Plum Tree Island

Area1 is southeast of Plum Tree Island with a known high anomaly concentration. These show up very well in the magnetometer data. Six strong EM61 anomalies also appear that are visually well-correlated with those in the magnetometer data. The traverses were cut short because the boat's propeller encountered a shallow submerged pile of concrete rubble.

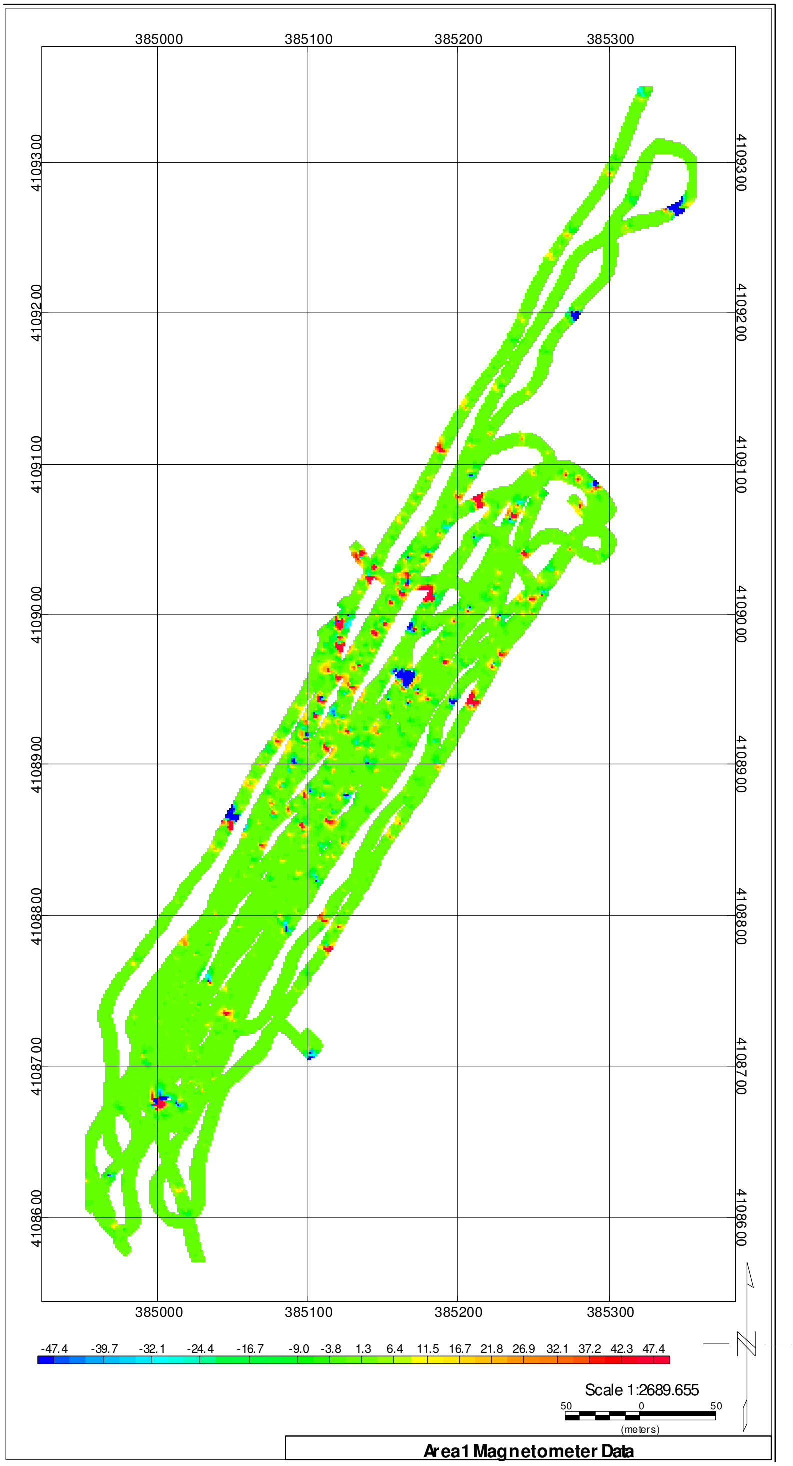

Figure 31: Magnetometer data (+- 50nT) from area1

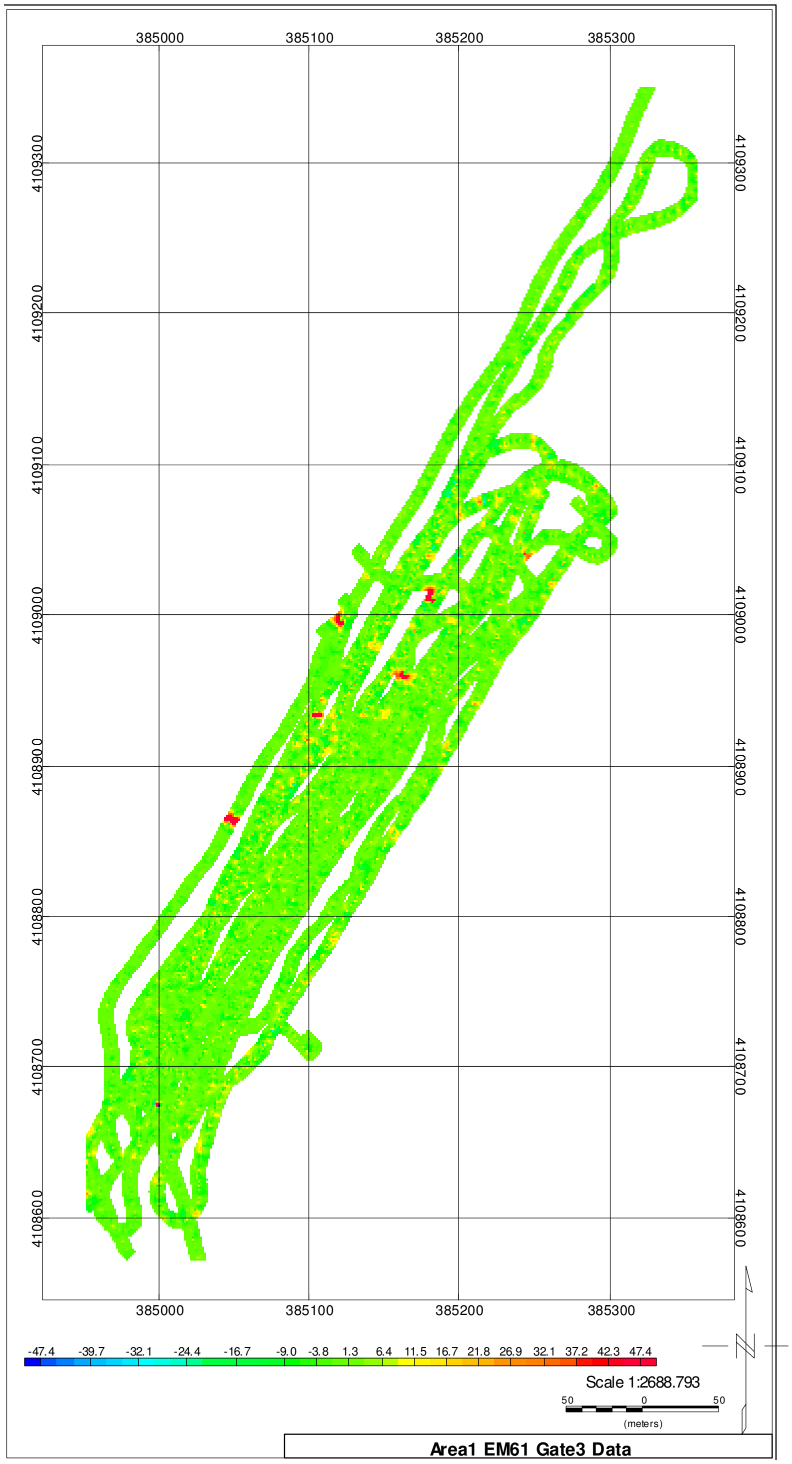

Figure 32: EM61 gate3 data (+- 50mV) from area1

Area3 is sparsely populated with anomalies in the magnetometer data, several of which correlate with weak anomalies in the EM61 data.

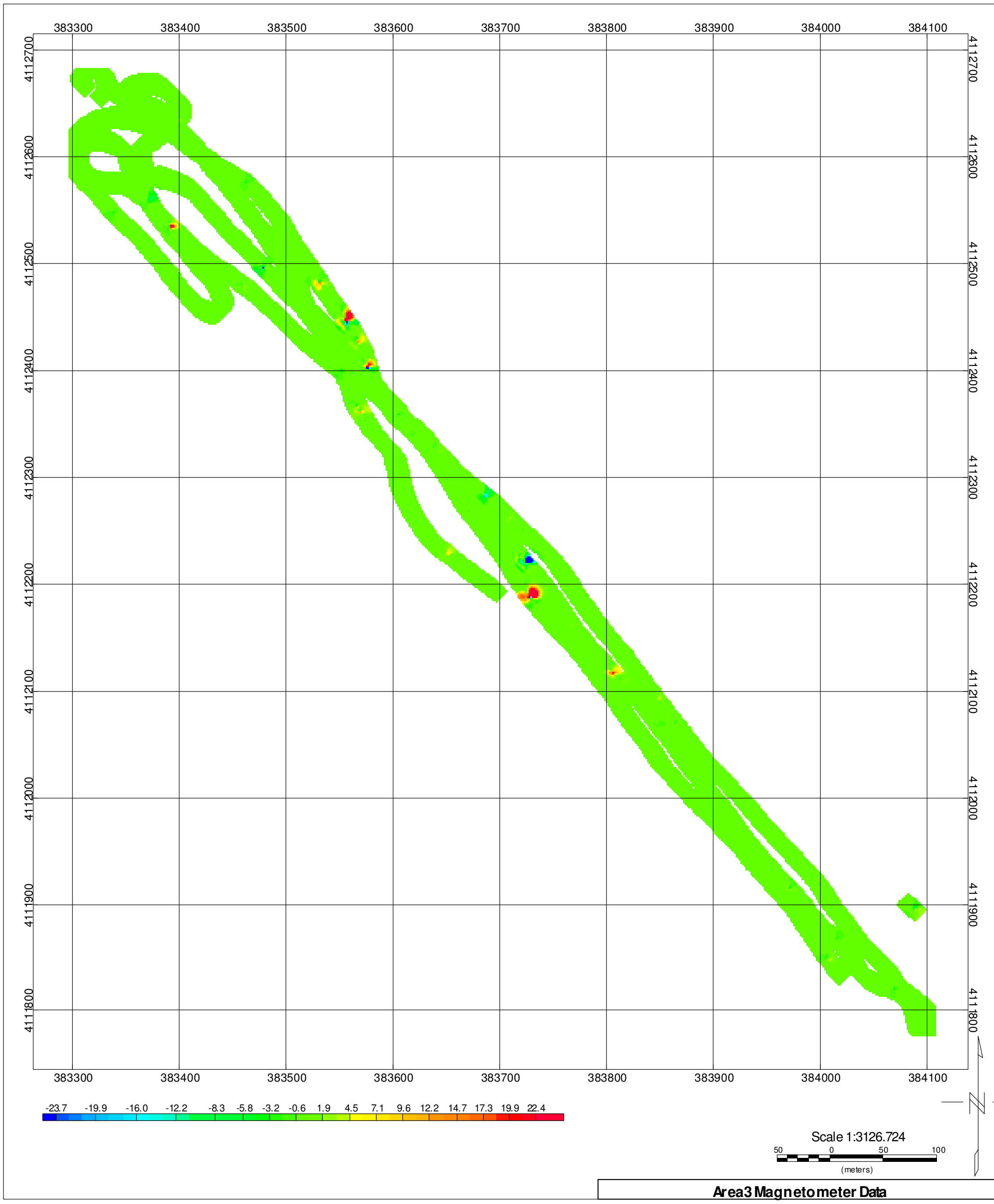

Figure 33: Magnetometer data (+- 25nT) from area3

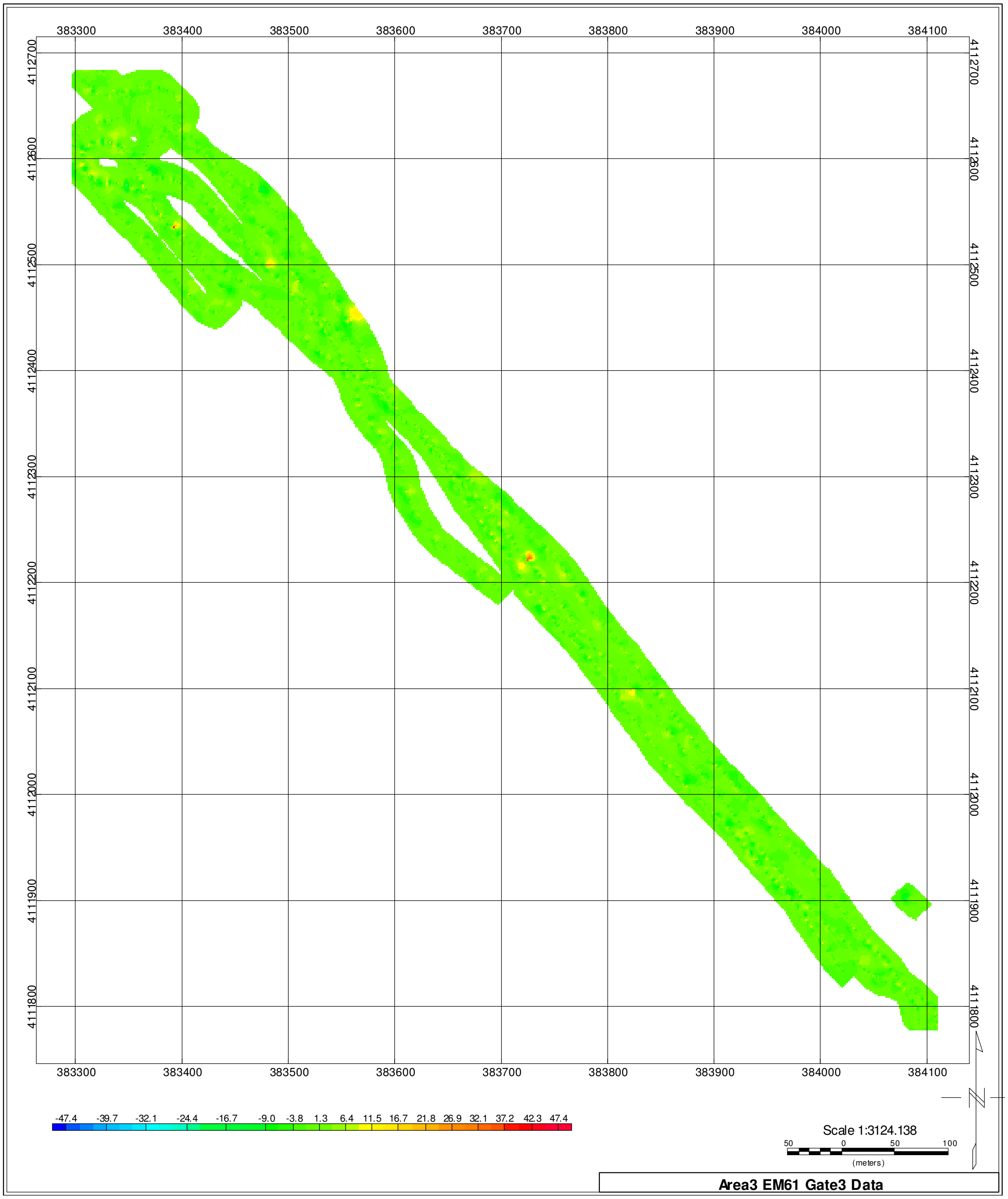

Figure 34: EM61 gate3 data (+- 50 mV) from area3

Area4 ha level in
the EM6

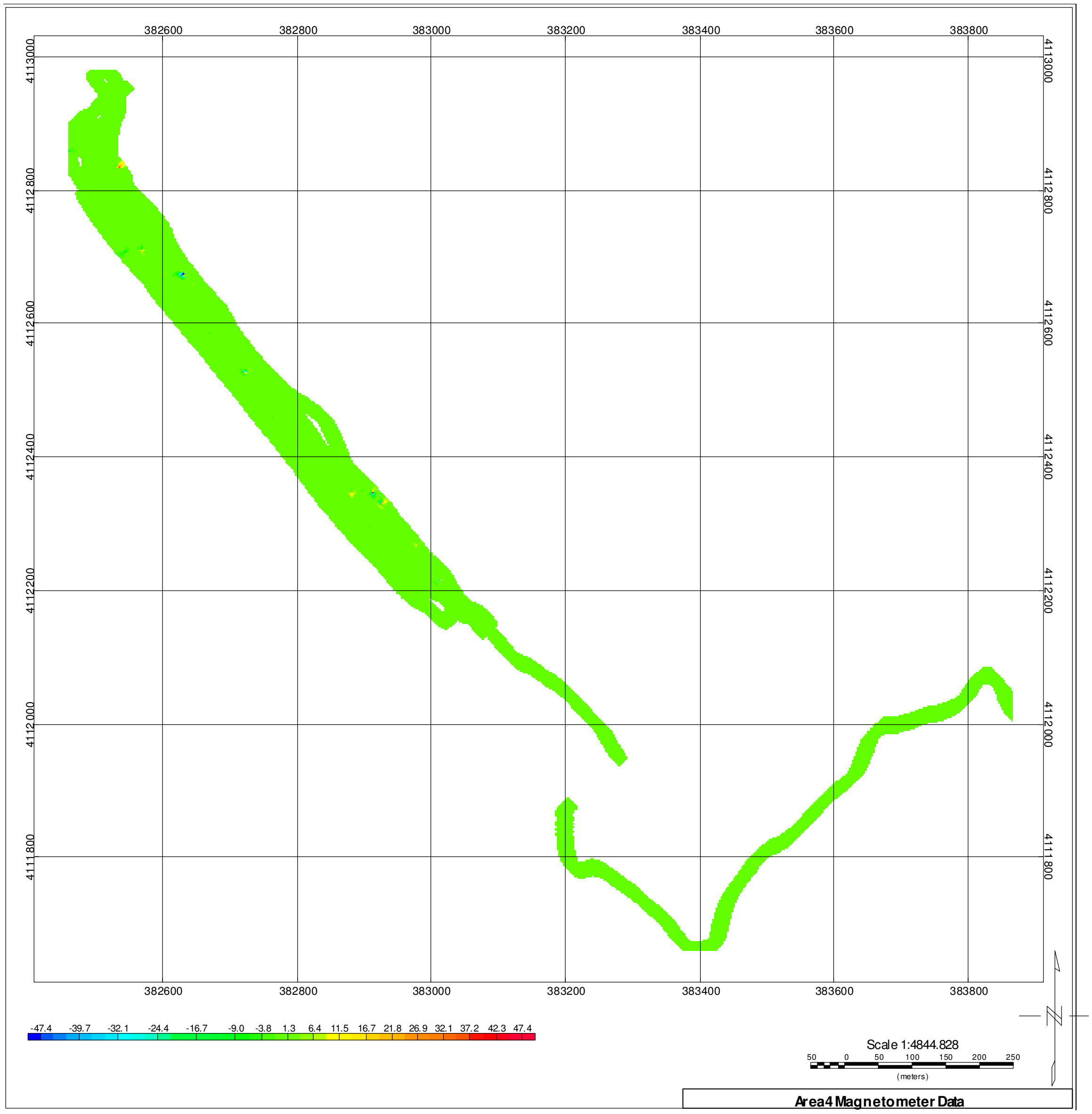

Figure 35: Magnetometer data (+- 50nT) from area4

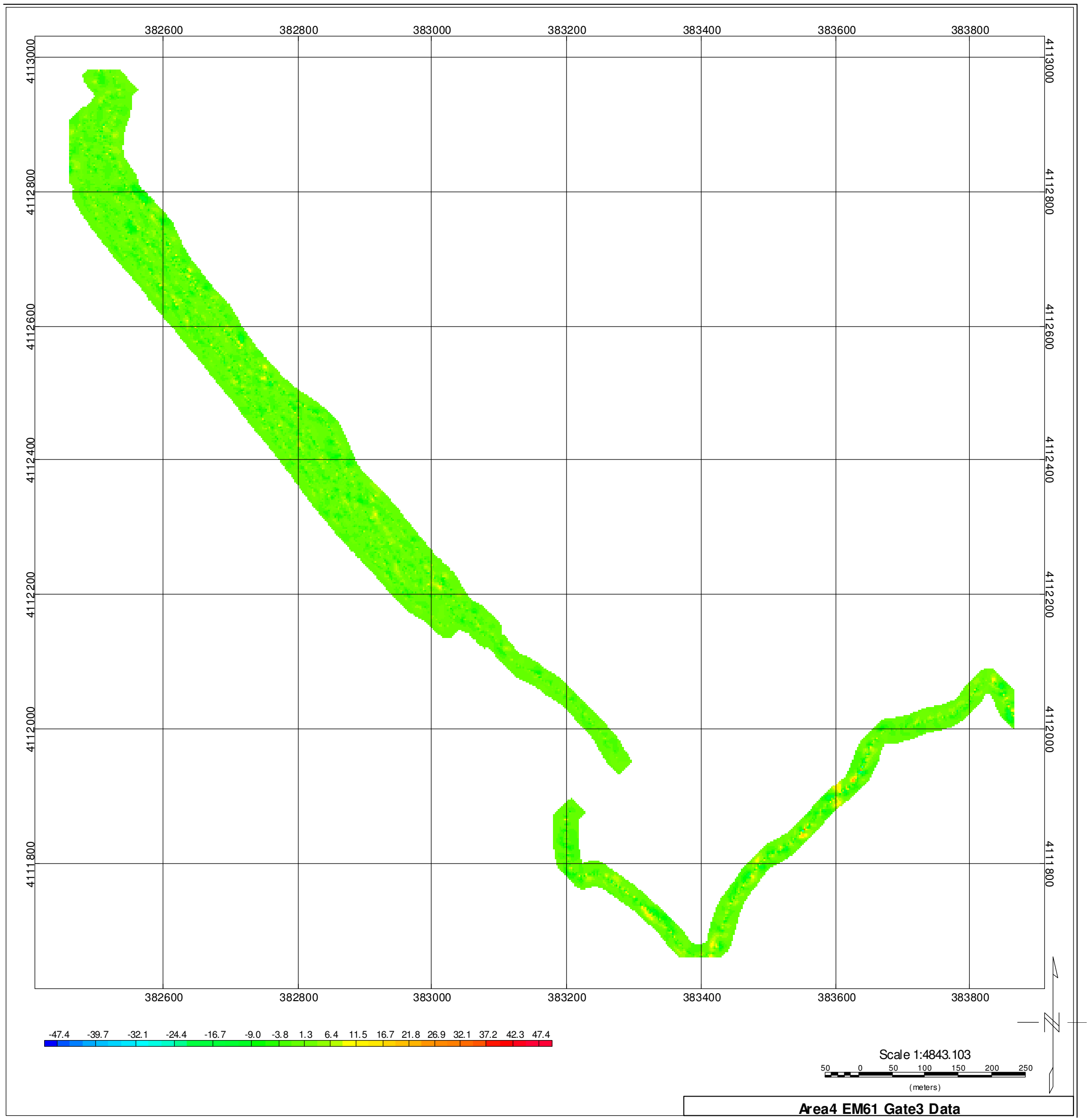

Figure 36: EM61 gate3 data 50 mV) from area4

Area5 is virtually anomaly-free in the magnetometer data, even at a +-25nT scale. Thus it is likely that any weak anomalies in the EM61 data are noise.

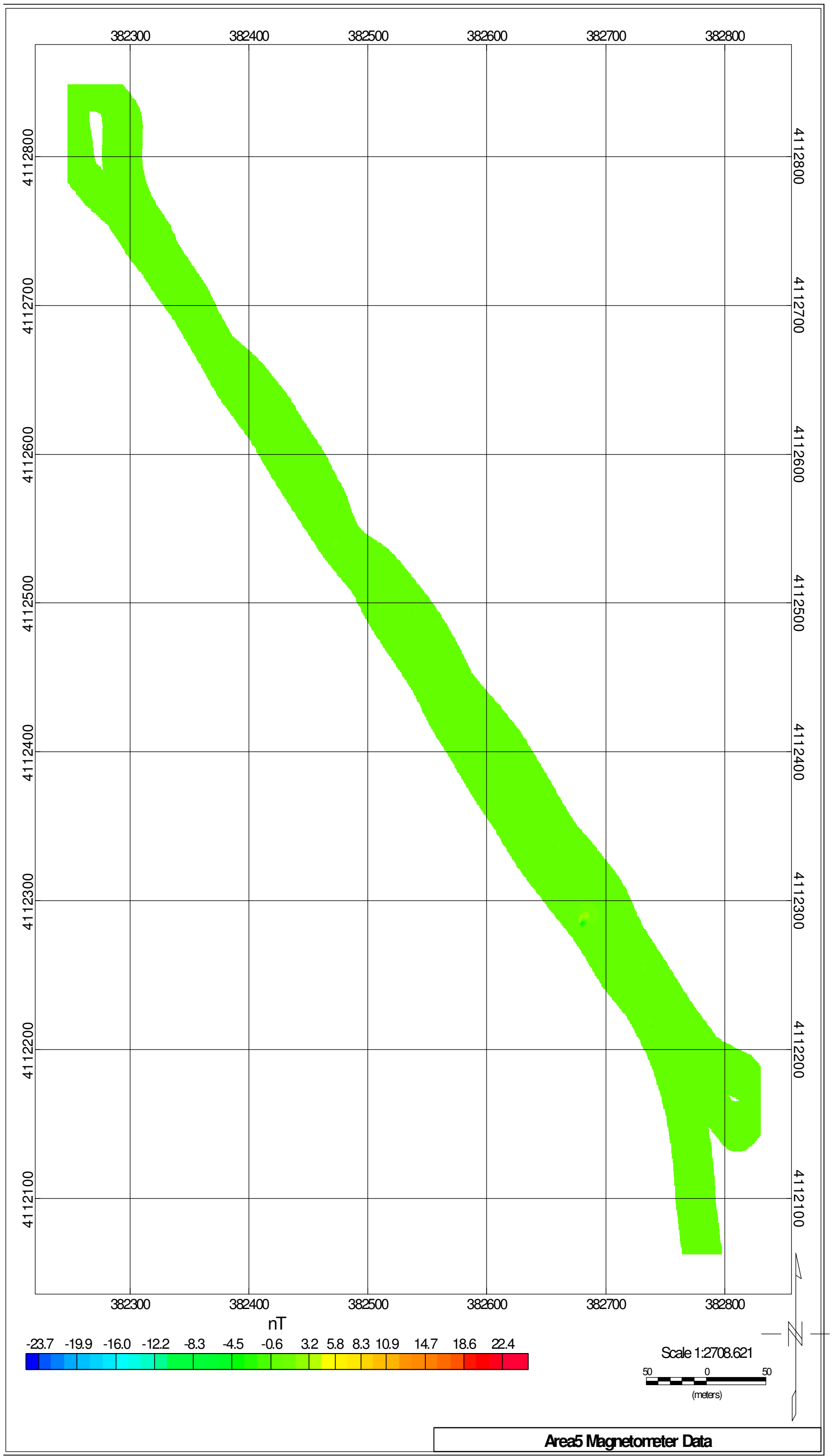

Figure 37: Magnetometer data (+- 25nT) from area5

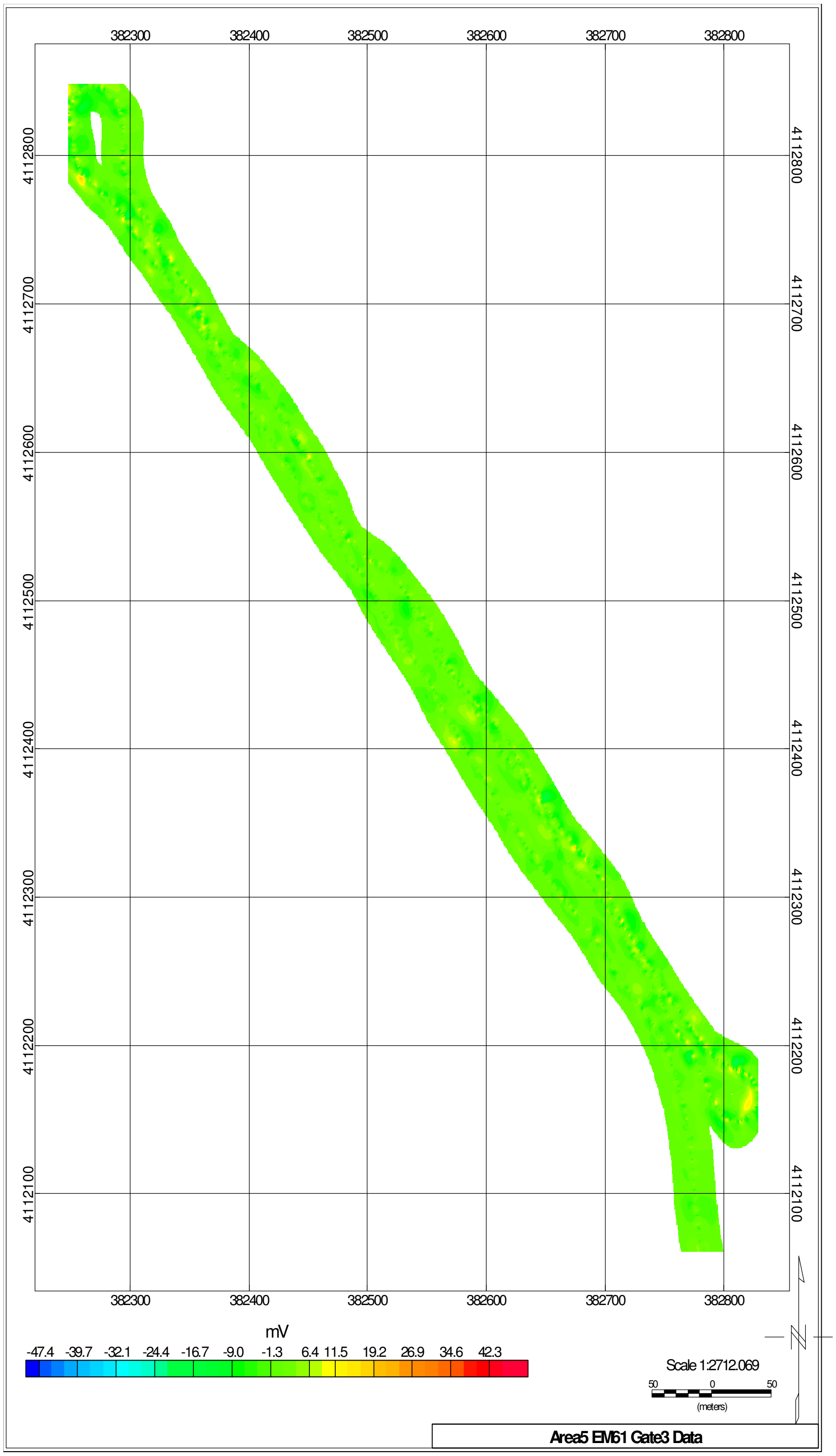

Figure 38: EM61 gate3 data (+- 50 mV) from area5

8 COST ASSESSMENT

8.1 COST MODEL

The cost model is shown in the table below.

Table 20: Cost model

Cost Element	Data to be Tracked	Estimated Costs
Instrument cost	Component costs and integration costs • Engineering estimates based on current development • Lifetime estimate • Consumables and repairs	$238,000
Mobilization and demobilization	Cost to mobilize to site • Derived from demonstration costs	$14,000
Site preparation	Test plot emplacement	$3,500
Instrument setup costs	Unit: $ cost to set up and calibrate Data requirements: • Hours required • Personnel required • Frequency required	$550 1 2 Daily
Survey costs	Unit: $ cost per hectare Data requirements: • Hours per hectare • Personnel required	$1,440 3.29 2
Detection data processing costs	Unit: $ per hectare as function of anomaly density Data Requirements: • Time required • Personnel required	$170 2 hours 1

Instrument Cost: Hardware cost estimates for USEMS are in the table below. The original proposal for USEMS did not include a GPS (the project was to use SAIC's GPS at no cost). However, the use of a Trimble MS860II heading receiver simplified things substantially, so a used unit was procured. GPS antennas, radio, and base station were loaned by SAIC. The $12k GPS cost represents the cost to purchase a used MS860II, antennas, and a radio. Cost of a base station is not included below, as subsequent use of USEMS will probably employ corrections from a Real Time Network (RTN) as was done at Plum Tree Island. An EM61 electronics console was loaned to the project by SAIC, but is included in the cost below. The mag interleaving box from MSEMS was officially used in USEMS as government transferred property, but a $25k cost is entered as an estimate if SAIC needs to build another.

A $106k contract to Brooke Ocean Technology funded the design and development of the towfish (absent the sensors and electronics). $20k represents an estimate that 20% of that cost was materials and fabrication and 80% was non-recurring engineering costs.

Integration costs to build another USEMS from scratch are estimated as a senior project manager, mechanical engineer, and technician full time for four weeks, and a software engineer full time for one week, totaling approximately $80k.

This results in an estimate of $238k for duplication costs.

Table 21: Estimated USEMS component costs

USEMS Components		
Boat	17' Carolina Skiff	$20,000
Computer	Aaeon 6920	$2,500
Monitor	Argonaught	$1,500
Towbar and bridle	Forte Carbon Fiber	$3,000
EM61 electronics console	Geonics	$10,000
EM61 submersible coil	Geonics	$8,000
EM61 submersible cable	Geonics	$3,000
G882 Magnetometer and cabling	Geometrics	$30,000
MagLog software	Geometrics	$3,500
Inclinometers and cabling	Advanced Geomechanics	$4,000
Diveplanes and hydraulics	Various	$5,000
Rotary positioning sensors	Penny&Giles	$1,500
Trimble MS860II	Trimble	$12,000
Depth charter	Humminbird	$1,500
Towfish housing	Brooke Ocean Technology	$20,000
Mag interleaving box	SAIC	$25,000
Transom mount	LeCam	$2,000
Transom pivot	LeCam	$4,600
Boom attachment	LeCam	$1,000
Integration		$80,000
Total		**$238,000**

We estimate the lifetime of the system as five years.

It is too early to estimate repair costs. We experienced one mechanical failure at Plum Tree Island – a broken tab where the bridle attaches to the boom due to inadequate strength in the composite material. The component is being redesigned using different composite material.

Consumables are simply the fuel for the boat.

Mob/Demob: The cost of mobilizing USEMS from Waltham MA to Plum Tree Island VA and back, adjusted for a projected two-man crew, was approximately $13k.

Site Preparation: No site preparation was necessary for the USEMS survey. If the cost of putting in the test plot is part of site preparation, a day of field time was approximately $3500.

Instrument Setup Costs: Instrument setup time at Plum Tree Island was approximately half a day. Thus we estimate the cost as an hour of two people, or approximately $500.

Survey Costs: We estimate the coverage rate, and the resulting cost per hectare, assuming six hours per day of on-the-water data collection, an average speed of 1.5 meters per second, an efficiency factor of 75% (that is, 25% of the time spent turning around between lines), and a crew of two. The results are shown in the table below.

Table 22: Coverage rate calculation

speed (meters/sec)	1.5
hours/day	6
linear meters	32400
efficiency factor	0.75
square meters/day	24300
hectares/day	2.43
hours/hectare	3.29
cost/day	$3,500
cost/hectare	$1,440

Detection Data Processing Costs: USEMS data are read into the program "usemsproc" for geolocation, but processing is no different from MSEMS data. Processing of EM61 data is no different than processing data from a COTS EM61; the data must be de-spiked, lag-corrected, and background-leveled. These steps are performed in usemsproc. USEMS' magnetometer data requires the additional step of notch-filtering out the instrument-specific 15 Hz hum (created by the 60 Hz ambient electrical hum aliasing at 15 Hz because it is sampled at 75 Hz). This is also performed in usemsproc. The magnetometer and EM61 data are then independently be read into Oasis, and thresholds are applied to the magnetometer and EM61 data to generate a mag dig sheet and an EM61 dig sheet. At present, however, there is not a turnkey method of combining these dig sheets. Different survey jobs have had different requirements. Terrestrial production surveys have tended to utilize EM61-derived target picks, with any additional unique magnetometer target picks added in by hand. However, due to the standoff of the fish from the bottom, the detection advantage clearly belongs to the magnetometer, and the practical role of the EM61 is uncertain. The costs are estimated assuming that it takes one person two hours to batch-process one day's worth of data and generate anomaly maps and dig sheets.

8.2 COST DRIVERS

Deployment of USEMS requires the equipment to be strapped to the deck of the boat, and the boat, on its trailer, to be towed to a survey site. The equipment is currently based in the Northeast. As such, West coast deployment would carry high mobilization cost. Because the equipment attracts a lot of attention when left in hotel parking lots, a private security guard is recommended.

If a USEMS area survey is conducted with a goal of detection of small munitions items, survey time and thus cost will likely increase in order to ensure coverage with very small amounts of missed area.

8.3 COST BENEFIT

USEMS is an alternative to cable-towed systems. It allows a towfish containing a magnetometer and an EM61 to be deployed close to the bottom and geolocated very accurately in very shallow (< 12 ft) marine environments. USEMS is not intended to replace larger cable-towed arrays in open, deeper areas, but is intended to augment cable-towed arrays where may have trouble with very shallow water and entanglements with obstacles such as buoys. As such, the benefit comes from being able to survey areas where previously there was no applicable survey tool.

9 IMPLEMENTATION ISSUES

9.1 COTS Versus Custom Equipment

Although all of the geophysical sensors, positioning sensors, and major subsystems in USEMS are COTS or near-COTS, USEMS as a whole is a custom-built prototype. The towfish, boom, bridle, dive planes, transom, and boom pivot with its rotary positioning sensors on all three degrees of freedom, are all hand-built. At present, the equipment is very tightly coupled, mechanically and electrically, to the 17’ Carolina Skiff. It would be a major engineering effort to, for example, transfer the towing rig and electronics to a vessel of opportunity.

9.2 Intended Operators and Training

At Plum Tree Island, the system was operated by its inventors, as is appropriate for a dem-val survey. For subsequent surveys, USEMS can be operated by a lightly-trained crew consisting of a boat pilot with experience in driving parallel lines, and a geophysical technician with experience acquiring GPS, EM61, and magnetometer data in MagLog.

9.3 Deployment of Towfish and Boom

During USEMS’ design, we were mindful of the requirement that the fish and the boom be able to ride on the deck of the boat until the boat reached the survey area, and be deployed in the water at the survey area. As designed, we envisioned the survey area deployment of USEMS’ fish and boom to occur with the boom being attached to the fish while both were on the deck of the boat, then the pair of them winched into the water with the jib crane, then the top end of the boom attached to the transom mount by an operator inside the boat and leaning out. In practice, however, we’ve found that the best way to deploy the fish and boom is to put them both in the water, put a USEMS operator into a small inflatable, and have him attach the fish to the boom and then the boom to the transom mount. At Plum Tree Island, we deployed the system this way every morning; it takes perhaps 15 or 20 minutes. However, at Plum Tree Island, because the test plot was so close to the marina, we deployed the equipment dockside at the marina. We do not minimize the degree of difficulty in deploying in this fashion in heaving seas. However, the greater issue is that USEMS is designed for operation in Sea States 0 or 1. It is going to be difficult deploying the gear whether one is winching just the fish, or the fish and the boom, into the water in anything other than calm conditions. For this reason, in a real survey, whether the equipment is deployed dockside or deployed at the survey site will be a function of the distance and the sea state.

9.4 Use of GPS Real Time Network (RTN) to Eliminate Need for Base Station

Because a portion of the demonstration included surveying off Plum Tree Island, and because Plum Tree Island is a restricted area, it was necessary to develop a solution for GPS deployment that did not require physically placing a base station on Plum Tree Island. For this reason, we utilized a Real Time Network (RTN) solution that accessed RTK corrections available over the Internet. The USEMS computer was outfit with a COTS USB cellular thumb-sized modem activated with an account and a data plan, enabling Internet access. A one-month account was taken out with Earth Vector Systems (EVS), who maintains a network of base stations along the East coast. A piece of widely-used freeware (GNSS Internet Radio) was employed as client software to connect over the Internet to EVS, obtain the corrections, and output them, via one of the computer's serial ports, to the Trimble MS860II receiver. This configuration enabled RTK GPS data to be acquired without setting up a base station. However, the failure modes of the configuration were not well-understood at the start of the survey. Whenever there was an interruption in the cellular connection (akin to a dropped cell phone call), the GNSS Internet Radio client software would have to be restarted. The client software had the ability to automatically try to reconnect, but in order to know which base station is nearest, the client software has to be told the approximate location of the rover. This can be done manually, but that precludes the ability to automatically reconnect. It is possible for the GPS to send the client software a NMEA string with the current position, but because all ports of the GPS are occupied (one goes to MagLog; the other goes to the guidance system) this requires building a serial adapter that splits the receive and transmit lines and sends them different places. We constructed this adapter during the demonstration, and with the ability to automatically restart when the cellular connection was dropped, the RTN solution became more robust. For a subsequent survey, we would not use the thumb-sized USB modem and instead would employ one of the models utilizing a more sensitive external antenna.

9.5 Line Following and Display of Bathymetric Data

The ability to follow pre-planned lines on the shallow water test site turned out to be the major challenge of the demonstration. As we described above, because we previously had success with a Trimble agricultural product (the EZ Guide) in terrestrial surveys, we thought it would be applicable here. The EZ Guide is COTS, small, inexpensive, sits directly in the boat operator's field of view, and gives clear on-track guidance feedback. We thought that this, combined with the traverse and GPS display in MagLog, and the traverse and bathymetric data displayed on the multifunction chart plotter ("fish finder"), would be more than sufficient. We now accept that the boat operator needs a general hydrographic survey, planning, display and guidance package such as HyPack, and that it needs to be mounted at the boat operator's station so the boat operator can interact with it in the same way he or she interacts with the chart plotter – that is, to choose among the myriad of configurable display options, depending on what he or she wishes to see.

One of the reasons that a package such as HyPack would be useful is that the COTS EZ Guide, chart plotter, and MagLog all have certain boundaries in their functionality. That is, the EZ Guide excels at presenting planned lines, GPS updates, and clear off-track information, but it won't allow you to read any data into it. This includes not only the reference line endpoints, but bathymetric data as well. Similarly, the chart plotter displays beautiful, high-resolution bathymetric data, but it won't allow you to read in pre-planned traverses, it doesn't display data from the external RTK GPS, and has no off-track indicator. MagLog will allow you to read in pre-planned traverses and overlay external RTK GPS data on them, but it too has no off-track indicator, and, incredibly, does not support direct read-in of high resolution NOAA bathymetric charts (neither does Oasis Montaj). Only HyPack (or similar) offers all this functionality together in one package.

Still, a seventeen-foot boat, moving at speeds of 1 or 2 knots, is buffeted about by wind, wave, current, and wake. In calm conditions, with an experienced operator, USEMS will probably do a good job at area coverage. But there will be conditions where it is likely that it won't, or only will for directional surveying (ie, into the wind).

9.6 Usefulness of EM61 Data Versus Magnetometer Data

In terrestrial MEC survey work where the majority of items are shallow, their size is small to medium, and sensors can be deployed very close to the ground, pulsed EM sensors (particularly the EM61) have been the sensor of choice for nearly 15 years. Magnetometers continue to be the sensor of choice for high-standoff applications such as airborne or underwater where their $1/R^3$ response is necessary (an EM sensor's $1/R^6$ response makes it less well suited than a magnetometer for high-standoff applications of ferrous objects). Because USEMS simultaneously deploys both a magnetometer and an EM61, we are able to see the response of both sensors in the underwater environment. In the shallow test plot, the standoff above bottom was small (about 0.5 meters), thus most objects were readily detectable by both sensors. On the deep test plot, where we collected data at standoffs of 1.0 and 1.5 meters, the signatures in the EM61 data became vanishingly small. In a signal-to-noise sense, this was caused by both the high EM61 noise present on the Plum Tree Island survey, as well as the decreased signal from the 1.0 and 1.5 meter sensor standoff. Since the Plum Tree Island survey, we have made modifications to the boat and EM61 wiring that have dramatically reduced the EM61 noise levels. For this reason, we expect EM61 noise levels to be nominal on the next survey.

On a terrestrial survey, if the target of interest is non-ferrous or low-ferrous (e.g., 20mm or 40mm projectiles), then the EM61 is the sensor of choice for detection. However, even on a terrestrial survey, reliable detection of these objects requires careful adherence to data quality objectives such as reduced sensor height, line spacing, missed area, and noise. This demonstration survey has shown that maintaining those particular data quality objectives is challenging in the underwater environment.

9.7 Correcting Hydrodynamic Instability

It is likely that the slight vertical hydrodynamic instability that appeared to be present in very shallow water can be corrected prior to the next survey. If the instability is a function of the towfish being in the motor's propeller wash, it is possible that simply angling the motor upward may mitigate the problem.

9.8 Regulatory Issues

Since the sensors (magnetometer and EM61) are already accepted by the regulatory community, there should be no regulatory hurtles to acceptance and use.

9.9 Current Availability of the Technology

USEMS is government-owned and is ready for field use. It can be provided as government furnished equipment to DoD contractors but would require trained operators. The developers from SAIC should be part of any survey teams in the first deployments of this system, either as prime contractor or as a sub-contractor to another DoD prime contractor.

10 REFERENCES

Siegel and Enriquez, “USEMS Plum Tree Island Demonstration Test Plan,” 2010.

Siegel, Richard, and Schwartz, “USEMS Final System Design Document,” 2009.

Appendix A: Points of Contact

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